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USAAVLABS TECHNICAL REPORT 68-12

GAS TURBINE ENGINE POWER AUGMENTATION AND EMERGENCY RATING

By

R. E. Dugas

April 1968

U. S. ARMY AVIATION MATERIEL LABORATORIES FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02 67-C-0002

GENERAL ELECTRIC COMPANY

LYNN, MASSACHUSETTS

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DEPARTMENT OF THE ARMY
U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA 23604

This report was prepared by the General Electric Company under the terms of Contract DAAJ02-67-C-0002. It consists of an analysis of methods for obtaining altitude hot day and emergency one-engine-out power.

The objectives of the program were to investigate and define optimum methods and/or designs for providing separate and combined altitude hot day and emergency power capabilities for future twin-engine gas turbine powered vehicles considering various engine design points.

The altitude hot day augmentation method required a capability of providing power for takeoff from a 6000-foot altitude on a 95°F day. This requirement was for a period of 5 minutes without a reduction in engine life or an increase in engine maintenance requirements.

The emergency power condition required that the augmentation method provide 90 percent of the total installed power for 1 minute, should one engine fail during a critical one-engine-out condition. This capability should allow a safe landing without damage to the vehicle, disregarding damage to the engine.

This report has been reviewed by the U.S. Army Aviation Materiel Laboratories and is considered to be technically sound.

Task 1M1Z1401D14415
Contract DAA J02-67-C-0002
USAAVLABS Technical Report 68-12
April 1968

GAS TURBINE ENGINE POWER AUGMENTATION AND EMERGENCY RATING

FINAL REPORT

BY

R.E. Dugas

Prepared by
ADVANCED TECHNOLOGY AND DEMONSTRATOR PROGRAM DEPARTMENT
GENERAL ELECTRIC COMPANY
LYNN, MASSACHUSETTS

For
U.S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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SUMMARY

Methods of obtaining altitude hot day and emergency one-engine-out power augmentation were analyzed.

The object of the program was to determine the performance and design requirement of the various augmentation methods available so as to allow selection of the optimum system for satisfying the divergent vehicle-engine power matching requirements which exist on helicopter-type vehicles between minimum cruise power, power for takeoff from 6000 feet on a 95°F day, and emergency one-engine-out takeoff power.

The approach taken in meeting this objective was to design a set of nine basic advanced technology engines defined from a set of prescribed requirements of airflow, engine type, ambient condition at takeoff, and level of technology; parametric cycle calculation; and mechanical design features which satisfied the restrictions imposed by the prescribed conditions.

In parallel with this effort, a large set of possible candidate augmentation methods was established by accepting suggestions from all available qualified sources. This list of candidate methods was reduced from its original level to a number suitable for detailed study by using a simple evaluation criterion to establish relative ratings among all similar schemes and then eliminating the inferior schemes from further consideration. Systems accepted for detailed study were analyzed thermodynamically and mechanically to establish their performance levels and the weight and complexity associated with each engine-augmentation system.

The combined engine-augmentation systems were then judged and rated on the basis of their ability to achieve the established augmentation goals; their complexity; any advantages, penalties, and limitations associated with their use; and a merit factor based on the total installed system and fuel weight required to perform a typical mission.

The ratings were based on the use of engines that had built-in physical and aerodynamic overspeed capability in their gas generators which were available for use in combination with any of the augmentation systems studied. This feature was included in this manner rather than as a separate augmentation system because most of the methods studied would result in gas generator overspeed unless some means of preventing it was used.

On the basis of the analytical studies, the optimum system selected consisted of a non-regenerative engine sized to take off unaugmented from 6000 feet on a 95°F day and equipped with pre-compressor, water-alcohol injection for emergency power. The suggested alternatives were also non-regenerative engines, using simple augmentation systems for altitude hot day takeoff and an auxiliary power source for emergencies.

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ERRATA

USAAVLABS Technical Report 68-12

"Gas Turbine Engine Power Augmentation and Emergency Rating"

Page 137, line 9 - change to read:

"horsepower at 3000 feet, 78°F can be calculated using the figures of Table VI as"

Page 137, 3d line from bottom - change to read:

$WF_1 = \underline{690} \times .085 = 58$ lb

BLANK PAGE

Figure		Page

Figure		Page

TABLES

SYMBOLS

BSFC	Specific fuel consumption based on power turbine work - lb fuel/hr/shp
ϵ, E	Regenerator or inter-regenerator effectiveness
H_2O_2	Hydrogen peroxide
K_4	Ratio of gas generator turbine inlet flow function with diaphragm varied to its value with nominal area setting
$\% N/\sqrt{\theta}$	Compressor percent corrected speed
P_3/P_2	Compressor pressure ratio
$\Delta P/P$	Regenerator or inter-regenerator total pressure loss (expressed decimally)
SHP	Power turbine output - hp
T_3	Compressor discharge temperature and combustor inlet temperature (all cycles) - °R
T_4	Gas generator turbine inlet temperature - °R
$\% T_4/\theta$	Gas generator percent corrected turbine inlet temperature
T_5	Gas generator turbine discharge temperature - °R
Wa	Compressor inlet airflow - lb/sec
W_E	Engine weight - lb
W_{L_3}	Regenerator leakage from air to gas side
W_L/Wa	Liquid air ratio in the compressor or combustor
W_{NH_3}/Wa	Ammonia air ratio injected in front of the compressor
W_W/Wa	Water or water alcohol to air ratio injected into the compressor or combustor
W_f	Fuel flow into the combustor - lb/sec

W_g	Turbine discharge gas flow - lb/sec
$\frac{Wa\sqrt{\theta_2}}{\delta_2}$	Compressor inlet corrected airflow - lb/sec
$\frac{W_4\sqrt{T_4}}{P_4}$	Gas generator turbine inlet flow function
$\frac{W_{51}\sqrt{T_{51}}}{P_{51}}$	Power turbine inlet flow function
ΔT	Temperature rise in interburner, or temperature drop in intercooler - °R
η_c	Compressor adiabatic efficiency
η_{t4}	Gas generator turbine adiabatic efficiency
$\frac{\eta_c}{\eta_c\ 100\%\ N}$	Ratio of compressor efficiency to compressor efficiency at 100 percent corrected speed
δ	Ambient pressure/ambient pressure at sea level

INTRODUCTION

Widespread deployment of gas turbine-powered helicopters and other vertical takeoff vehicles requires the vehicle power generating system to deliver takeoff power over a wide range of ambient temperatures and altitudes.

This requirement creates a problem in engine/vehicle power matching, which arises from two considerations. The first is that, while the takeoff power required remains high under all conditions, the power available from a gas turbine engine running at rated speed and turbine inlet temperature lapses considerably with the increases in altitude and ambient temperature. The second is that for the major portion of most missions flown the vehicle cruising speed is between 100 and 150 knots and the engine power required is only 50 to 75 percent of that required for takeoff from sea level on a standard day, and any oversizing of the engine to supply hot day altitude takeoff power results in an even lower percentage of power required for cruise. This increases the cruise specific fuel consumption and therefore the mission fuel required, reducing the useful load-carrying capacity of the vehicle.

Another similar matching problem is created if attempts are made to provide emergency power on a multiengine vehicle where the power required per engine can be increased by failure of one engine. One of the most demanding of such situations is that of one-engine failure during takeoff of a twin-engine vehicle.

Considering these problems, three possibilities present themselves: The first is the brute force method of selecting an engine large enough to supply the infrequently occurring maximum demand, accepting the full penalty in engine weight and fuel consumption which characterizes this approach. A second way is to select a power generating system consisting of an engine sized for normal takeoff or for somewhat lower than peak load demand, combined with an engine augmentation system which increases engine power output to meet the infrequently occuring maximum load requirement. The third method is to size the engine for normal takeoff power and then to provide an auxiliary engine for all higher load demands.

In the past, the oversize engine approach has been the most commonly accepted method of satisfying the maximum vehicle power requirements. Attention during the study has been directed primarily toward determining whether or not the engine augmentation approach might result in a better overall system when applied to advanced technology engines which satisfy the latest hot day takeoff and emergency one-engine-out power requirements. The engine and fuel requirements for a fully oversized engine have also been determined for use as a basis in evaluating the merit of the augmentation system. One auxiliary method was also evaluated as a means of obtaining emergency power.

To limit the scope and to give direction to the study, the power requirements were defined as follows:

1. Provide power for takeoff from a 6000-foot altitude where the ambient temperature is 95°F. This power is to be continuously available for 5 minutes duration and to be supplied in such a way that it can be used an unlimited number of times without reducing engine life or increasing engine maintenance requirements.

2. Provide emergency power during takeoff from sea level on a standard day such that if one engine of a twin-engine vehicle fails during the critical phases of takeoff, the remaining engine will supply continuously 90 percent of the total installed power for 1 minute. No restrictions were placed on the effect of emergency power use on engine life or maintenance requirements.

The following text describes the manner in which system evaluation was carried out, including selection of the advanced technology engines to which augmentation systems were applied, selection of promising augmentation systems and methods of mechanizing them, evaluation of merit factors of various engine augmentation combinations, and recommendations of optimum system.

BASIC ENGINE SELECTION

INTRODUCTION

The degree to which any given augmentation system is capable of increasing the power output from an engine is dependent, among other things, on the engine size, on its thermodynamic cycle, and on its mechanical design features. For example: the ability of an engine to use pre-compressor water injection is dependent on the compressor pressure ratio; the amount of liquid which can be evaporated in the combustor is dependent on the combustor temperature and the residence time of the liquid in the combustor, a function of combustor size; and the amount of temperature rise allowable in an interburner is dependent on the power turbine materials and cooling methods, if any, as well as the discharge temperature from the high pressure turbine, which depends on cycle pressure ratio and temperature. Since the validity and usefulness of the results of this study are then dependent on the basic engines to which augmentation is applied, the first phase of the study was a preliminary design investigation to define these engines.

METHOD OF APPROACH

This design phase was divided into cycle studies and mechanical design considerations, and the final engines selected were based on a compromise between optimum cycle performance and feasible mechanical configurations.

Prior to the start of the cycle studies, several parameters were preselected, limiting the required scope of the investigations. They were:

1. Engines considered were to be turboshaft designs.
2. The technology level was to be that predicted for engines starting into a demonstrator program in the 1967 - 1969 time period.
3. Engine airflow was set at 10 lb/sec
4. Engine design points were selected as
    a. Sea level standard day
    b. 6000 feet on a 95°F day
    c. 3000 feet on a 78°F day. This is a value which was selected by the contractor, who was given a choice of possible values between a and b. The basis of the selection was the fact that over the range of ambient conditions encompassed by the limits of a and b, the power loss due to changes in both altitude and ambient temp-

erature are almost linearly dependent on the changes which occur in going from a to b and selection of the third design point midway along this path provided the best curve through three points covering the span of ambient conditions that were investigated.

In addition, the requirement was established that both non-regenerative and regenerative engines were to be studied, and the decision was made to study two arrangements of regenerative engines. One arrangement had the regenerator located aft of the power turbine and one located between turbines in an arrangement called an inter-turbine regenerator. Schematic drawings of the thermodynamic flow sequence for the three engine types are shown in Figure 1.

In keeping with the idea of advanced technology engines capable of achieving significant improvements in engine performance, turbine inlet temperatures considered were limited to the range of values from 2200° to 2660°R. Levels of regenerator effectiveness were also placed near the upper limits possible.

Within the restraints imposed by these stated conditions, parametric cycle calculations were performed for each type of engine at each design point specified. A summary of all parameter variations and a list of the assumptions needed to define the cycle are shown in Tables I and II.

The results of the cycle computations were represented graphically (Figures 2 through 12) as specific fuel consumption versus shaft horsepower to assist in determining the optimum values of cycle parameters.

The method of approach to the mechanical design of the engines consisted of selecting components of the size and type required to achieve the desired thermodynamic performance and then making layouts containing these components in various arrangements to determine the problems associated with each configuration.

RESULTS OF DESIGN POINT STUDIES

Based on the cycle performance and mechanical design studies described above, nine engines were selected for use as basic engines to which to apply augmentation. The nine engines were one each of the three basic types sized at each of the three design points. The selections were based on providing performance as near optimum as mechanical and aerodynamic design considerations allowed. Summaries of the thermodynamic design values are contained in Table III, and mechanical design features are shown in Tables IV and V. Cross-sectional outlines of each engine type are shown on Figures 13 through 18.

Horsepower output calculations for each of the nine engines operating at each of the three design points are shown in Tables VI, VII, and VIII.

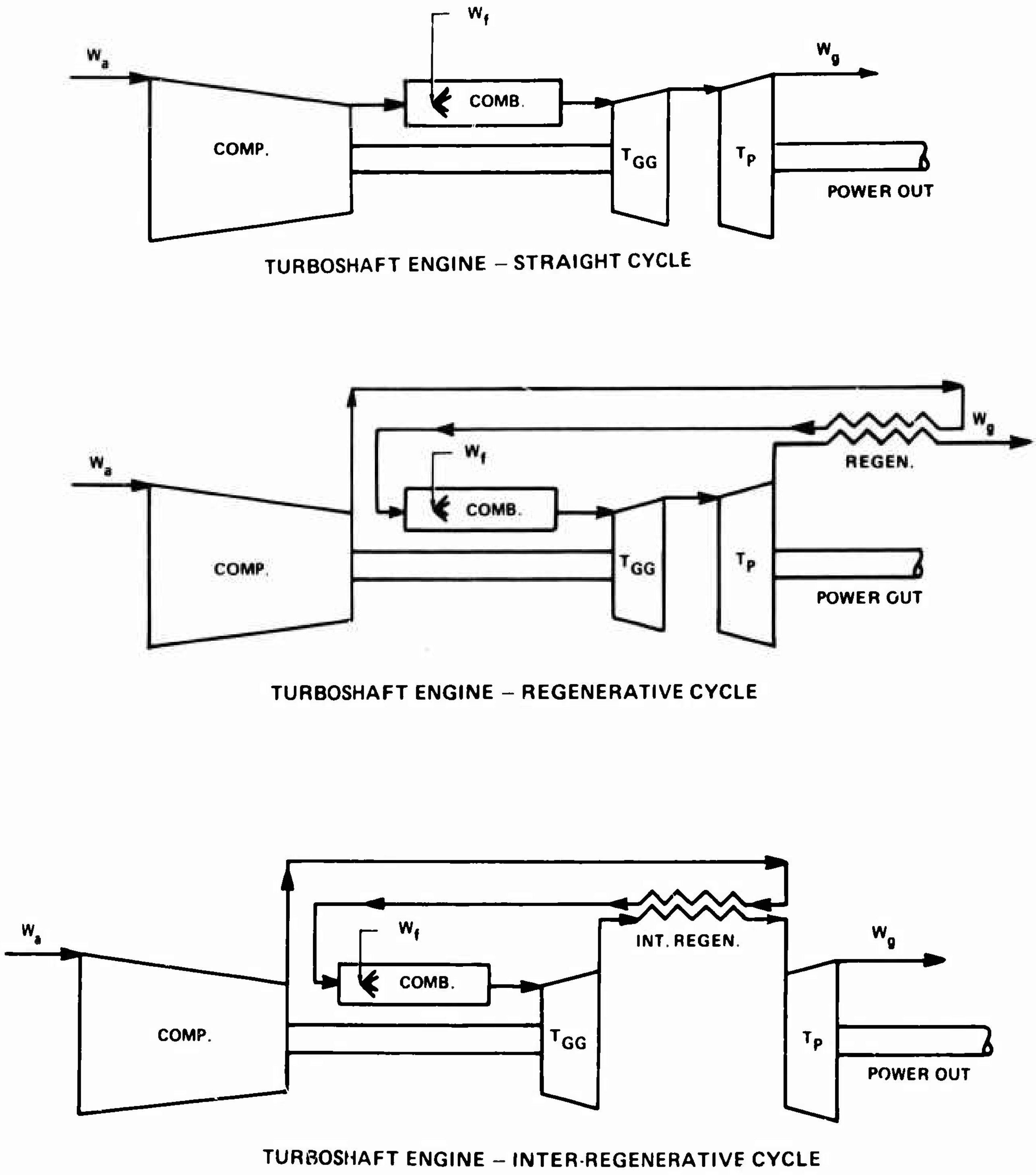


Figure 1. Thermodynamic diagram of cycles studied.

TABLE I

CYCLE PARAMETERS VARIED

Straight Turboshaft Cycle	
Parameter Varied	Values
P_3/P_2	10, 12, 14, 16, 18
T_4 °R	2260, 2460, 2660
Regenerator Turboshaft Cycle	
Parameter Varied	Values
P_3/P_2	5*, 6, 8, 10, 12
T_4	2460**, 2660
ϵ	.65, 70, 75, 80, 85
Δ P/P regenerator	.06, .08, .10 split 1/3 air side, 2/3 gas side
Inter-Regenerator Turboshaft Cycles	
Parameter Varied	Values
P_3/P_2	11, 13, 15, 17
T_4°R	2460**, 2660
ϵ	.70, .75, .80, .85
Δ P/P regenerator	.06, .08, .10 split 1/3 air side, 2/3 gas side

* Included for the 6000 ft, 95°F day only
** at SLS only

TABLE II CYCLE ASSUMPTIONS	
In performing the cycle calculations, the following component performance assumptions were made:	
Compressor inlet airflow	= 10 lb/sec
Compressor efficiency	= .88 polytropic
Compressor discharge leakage	= 0.1 lb/sec
Combustor efficiency	= 0.985
Combustor pressure loss	= 5 percent
Fuel heating value	= 18400 Btu/lb
Gas generator turbine efficiency	= 0.88 adiabatic
Turbine cooling flows are extracted at the compressor discharge.	
Total cooling flow was varied as a function of compressor pressure ratio (to account for variation in T_3) (using the equation $W_{c3}/W_2 = .162 + .000075\ T_4 + .0026\ P_3/P_2$)	
The cooling flow was returned to the cycle - 75 percent aft of the gas generator turbine and 25 percent aft of the power turbine.	
There is no energy loss associated with mixing the cooling flows and primary flows downstream of the turbines.	
Cooling flows do no work in the turbines that they cool.	
Power turbine efficiency	= 0.90 adiabatic
Tail pipe pressure loss	= 1 percent
Guarantee level multiplier on SHP	= 0.925
Guarantee level multiplier on BSFC	= 1.05
Flight speed	= 0 knots

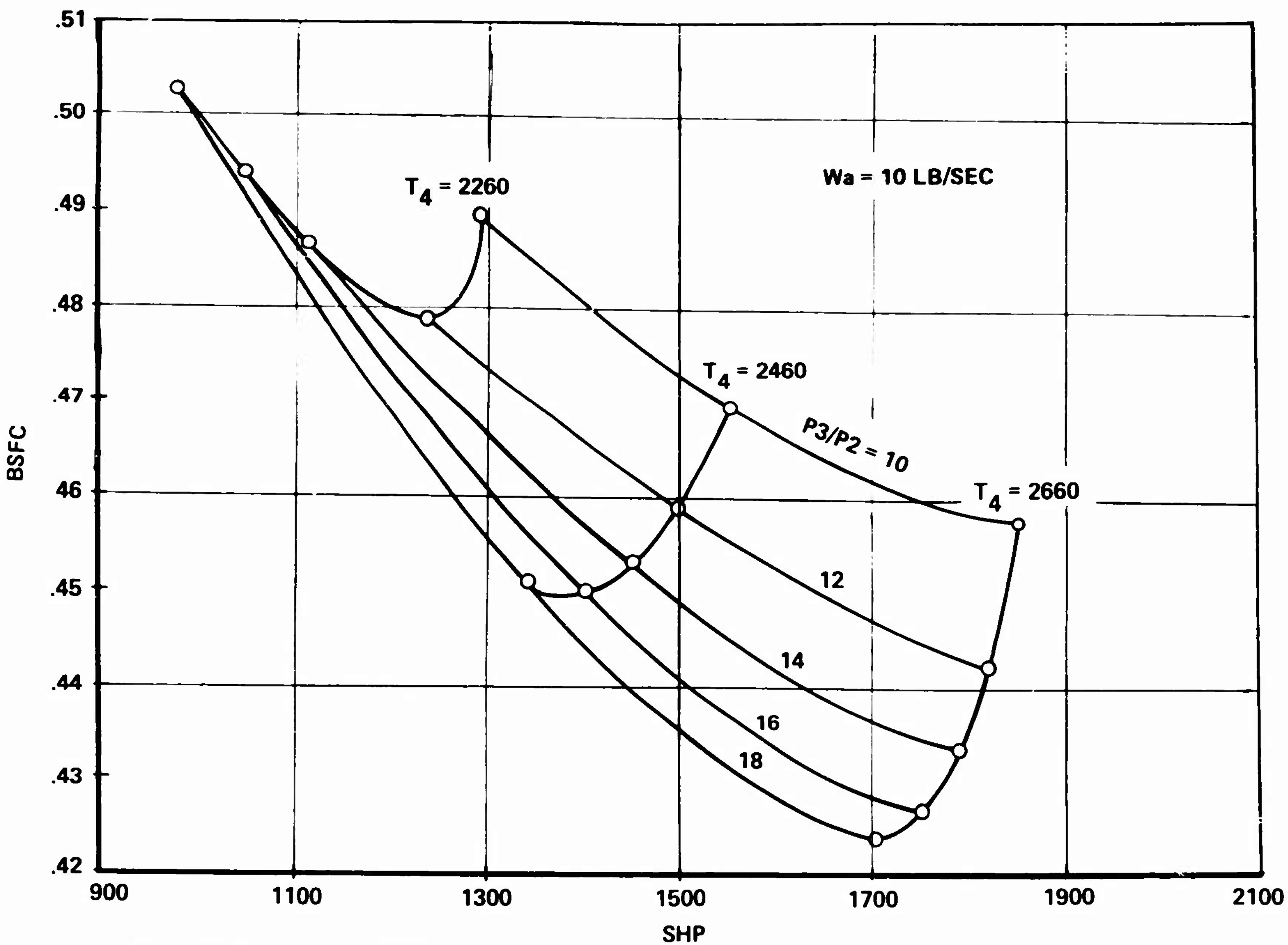


Figure 2. The effect of P3/P2 & T_4 on turboshaft engine SHP & BSFC, sea level static, standard day.

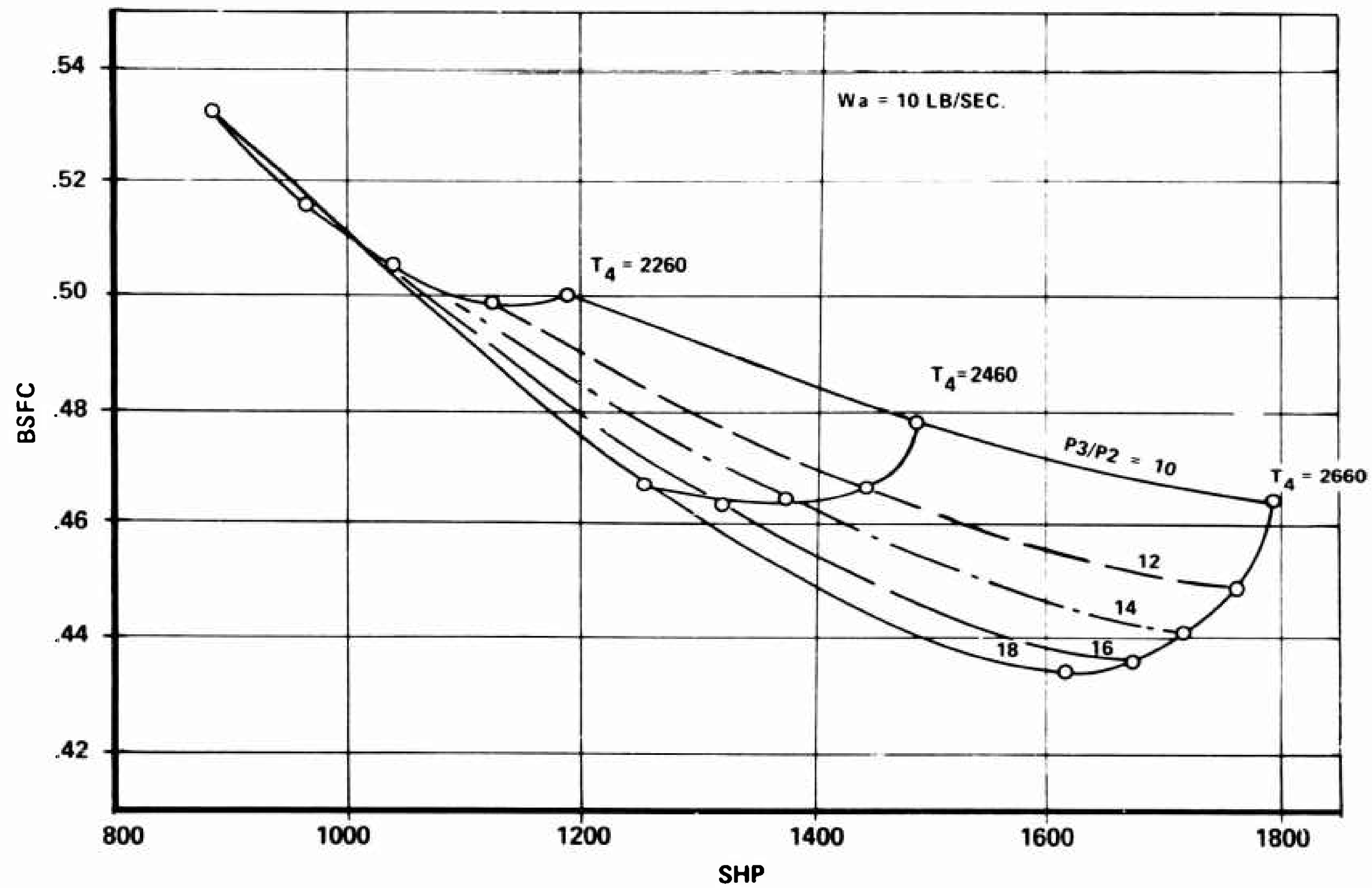


Figure 3. The effect of P3/P2 & T_4 on turboshaft engine SHP & BSFC, 3000 feet static, T ambient = 78°F.

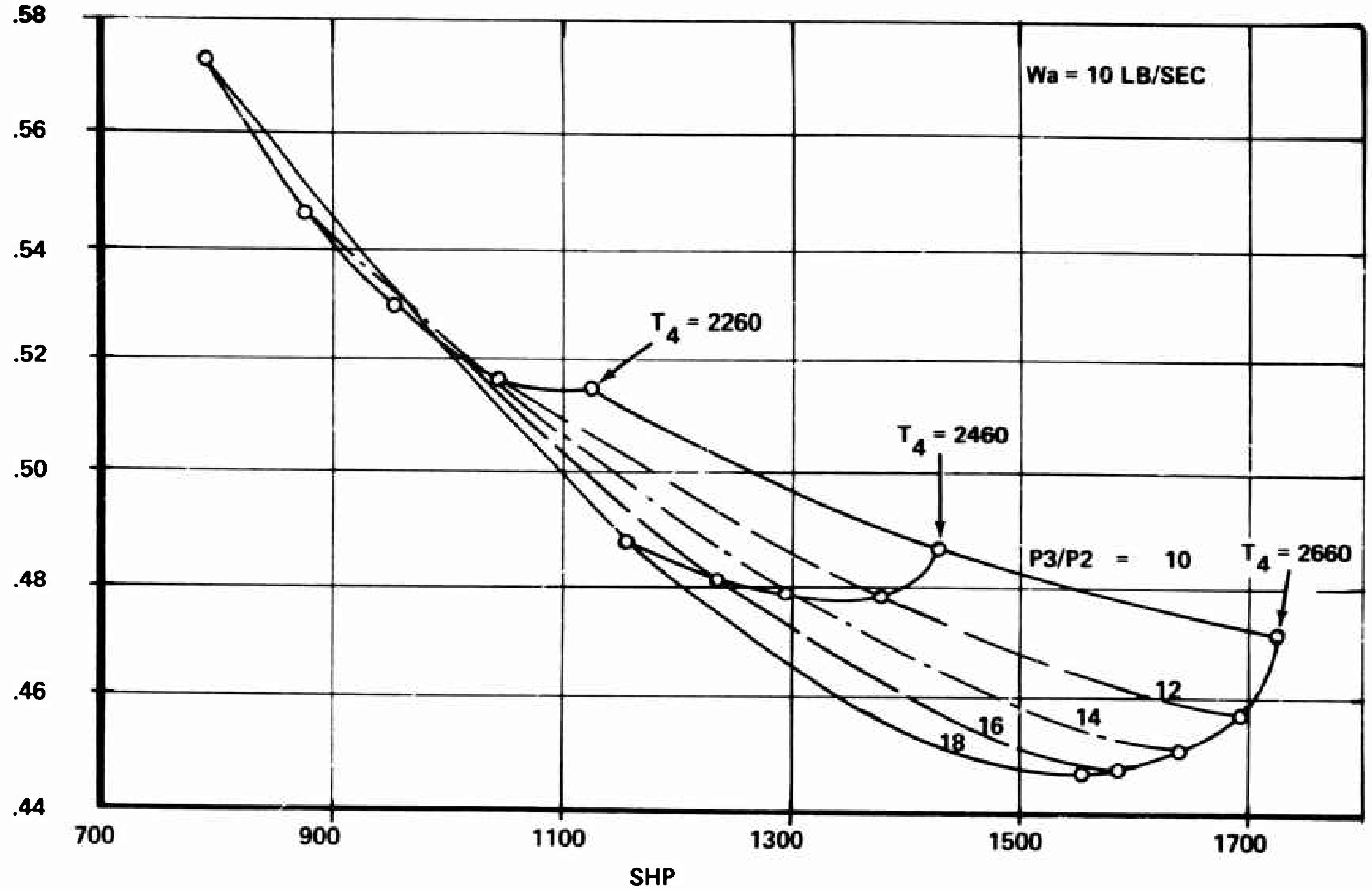


Figure 4. The effect of P3/P2 & T_4 on turboshaft engine SHP & BSFC, 6000 feet static, T ambient = 95°F.

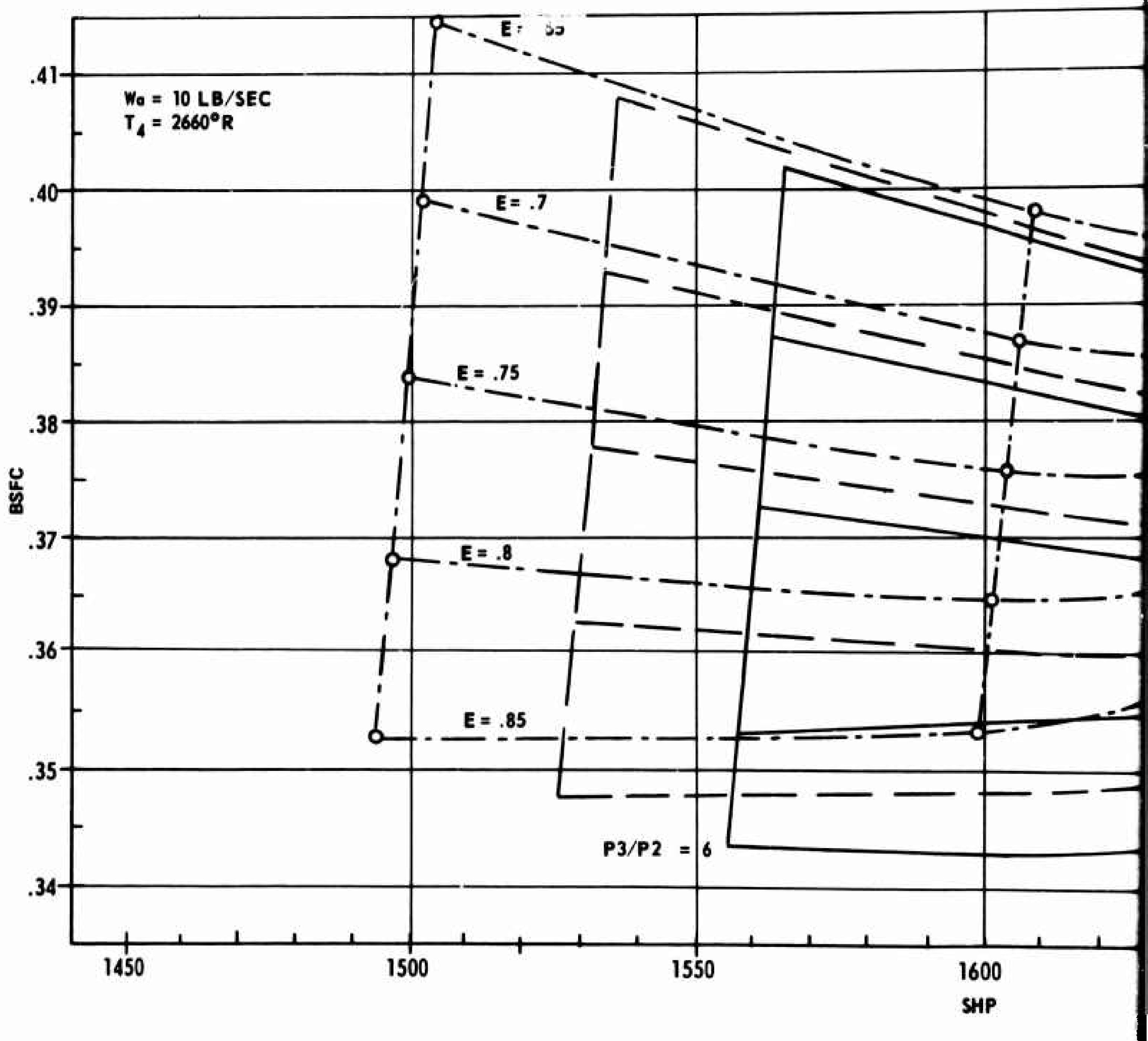
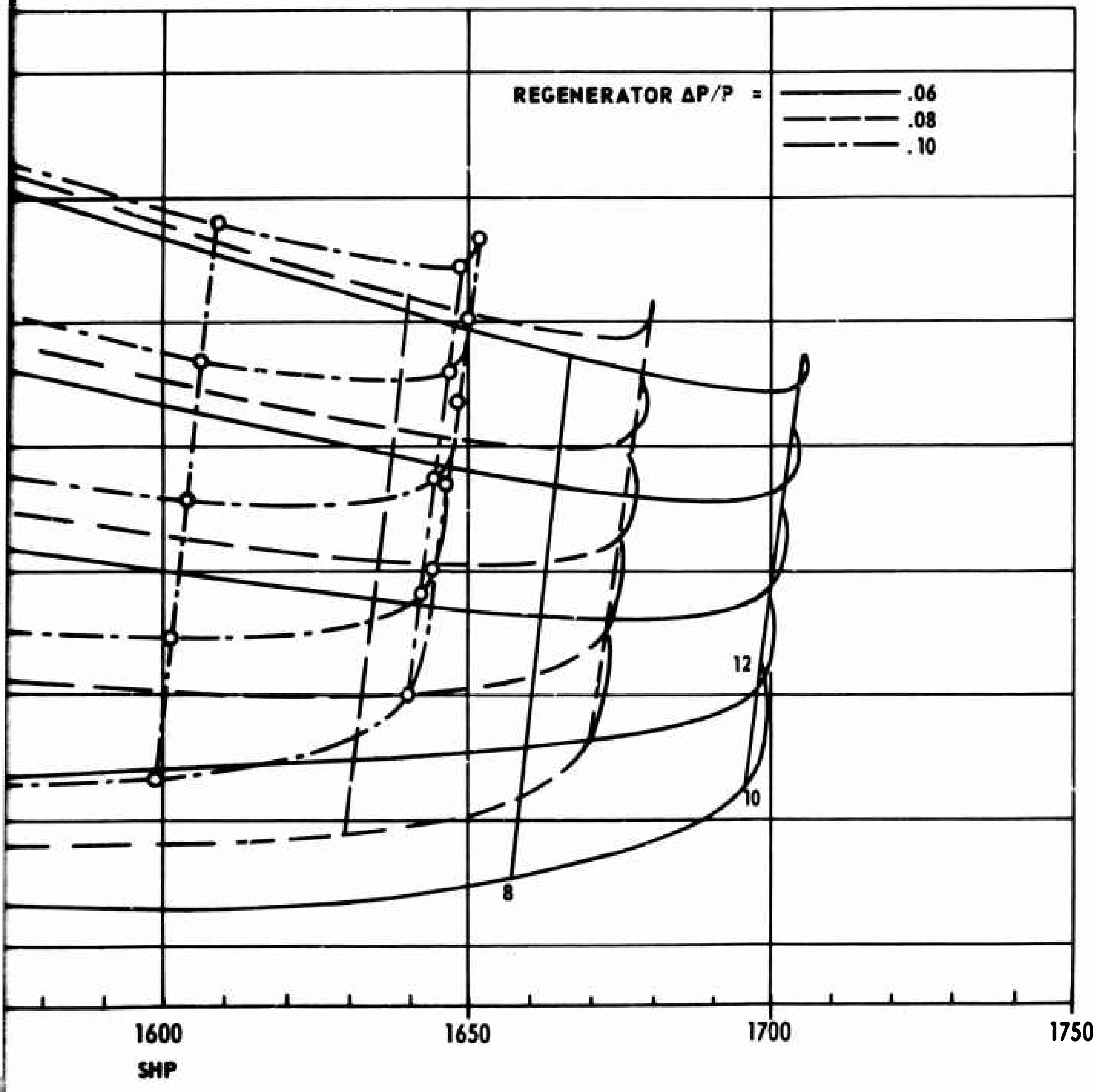


Figure 5. The effect of P3/P2, regenerator ΔP/P & regenerator effectiveness on regenerative engine SHP & BSFC, sea level static, standard day.



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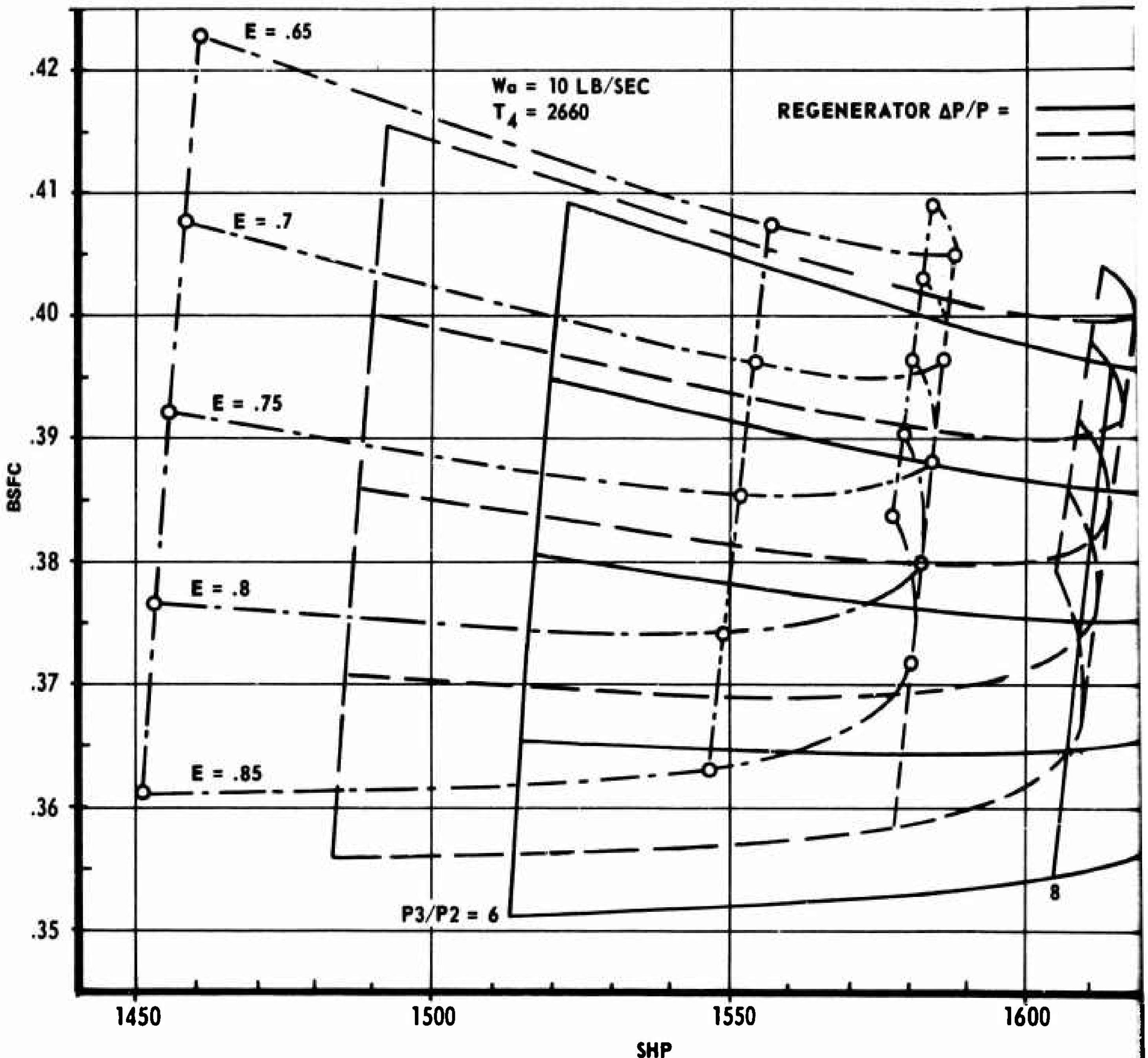

Figure 6. The effect of P3/P2, regenerator ΔP/P & regenerator effectiveness on regenerative engine SHP & BSFC, 3000 feet static, T ambient = 78°F.

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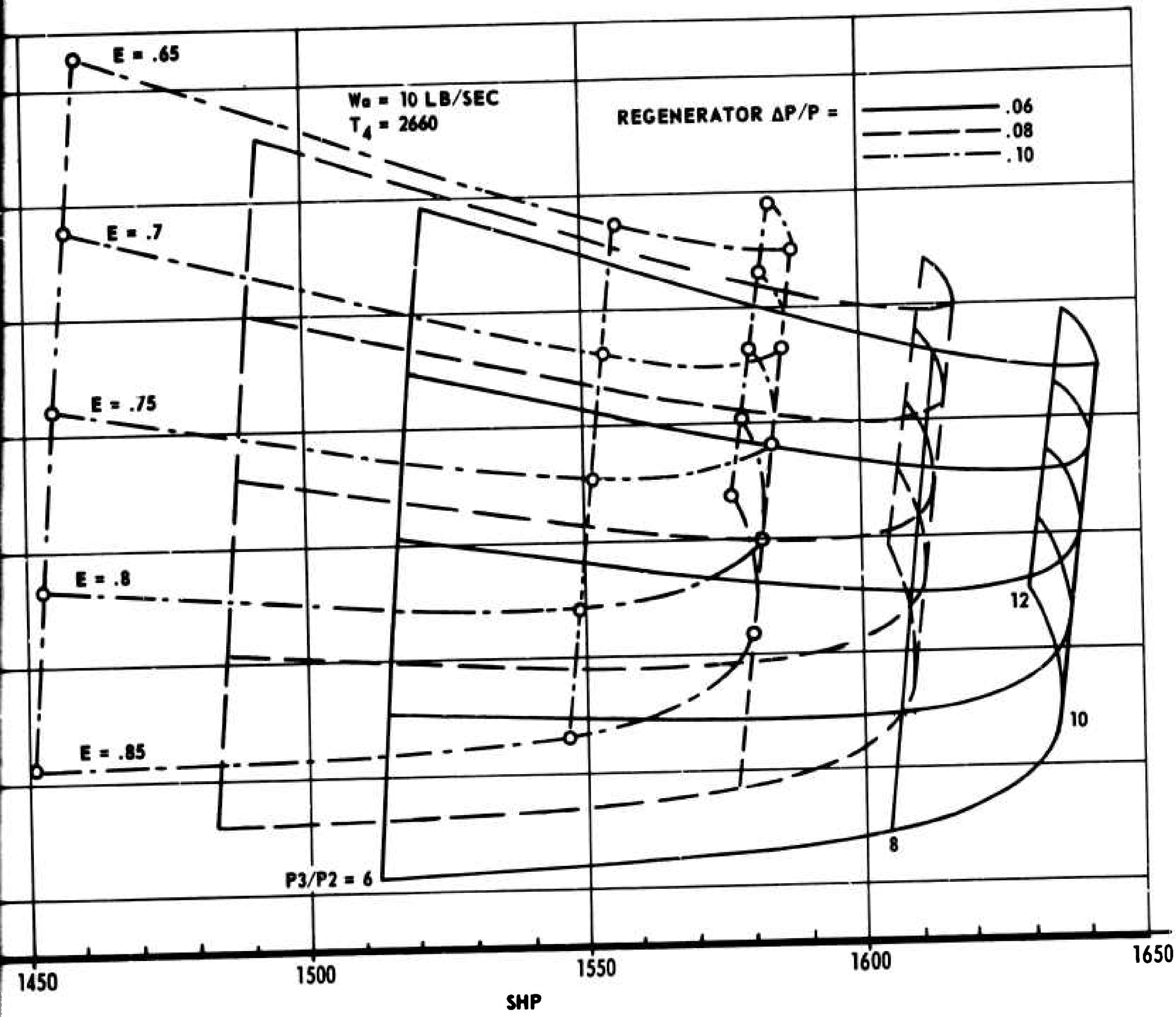

e 6. The effect of P3/P2, regenerator ΔP/P & regenerator effectiveness on regenerative engine SHP & BSFC, 3000 feet static, T ambient = 78°F.

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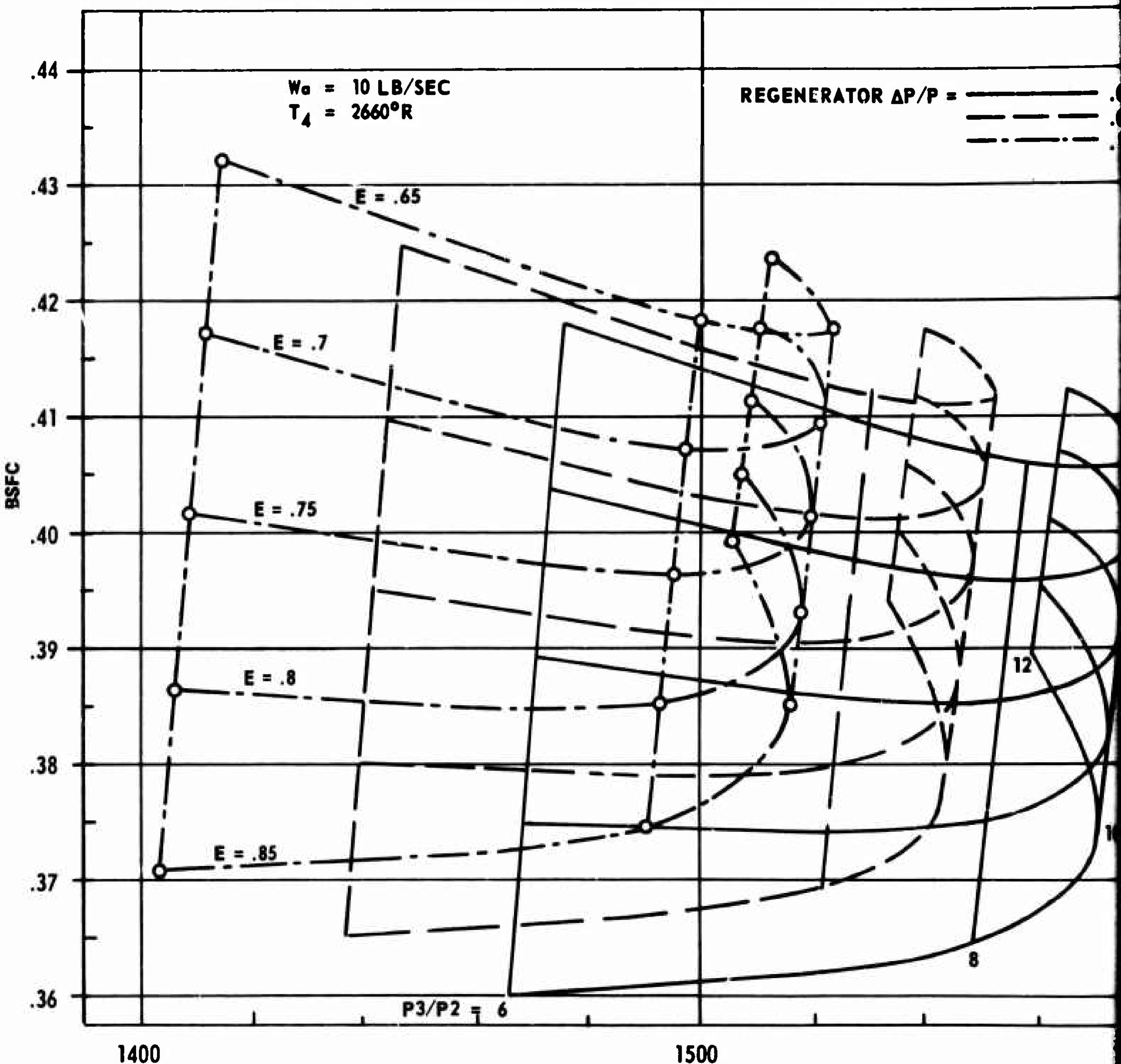
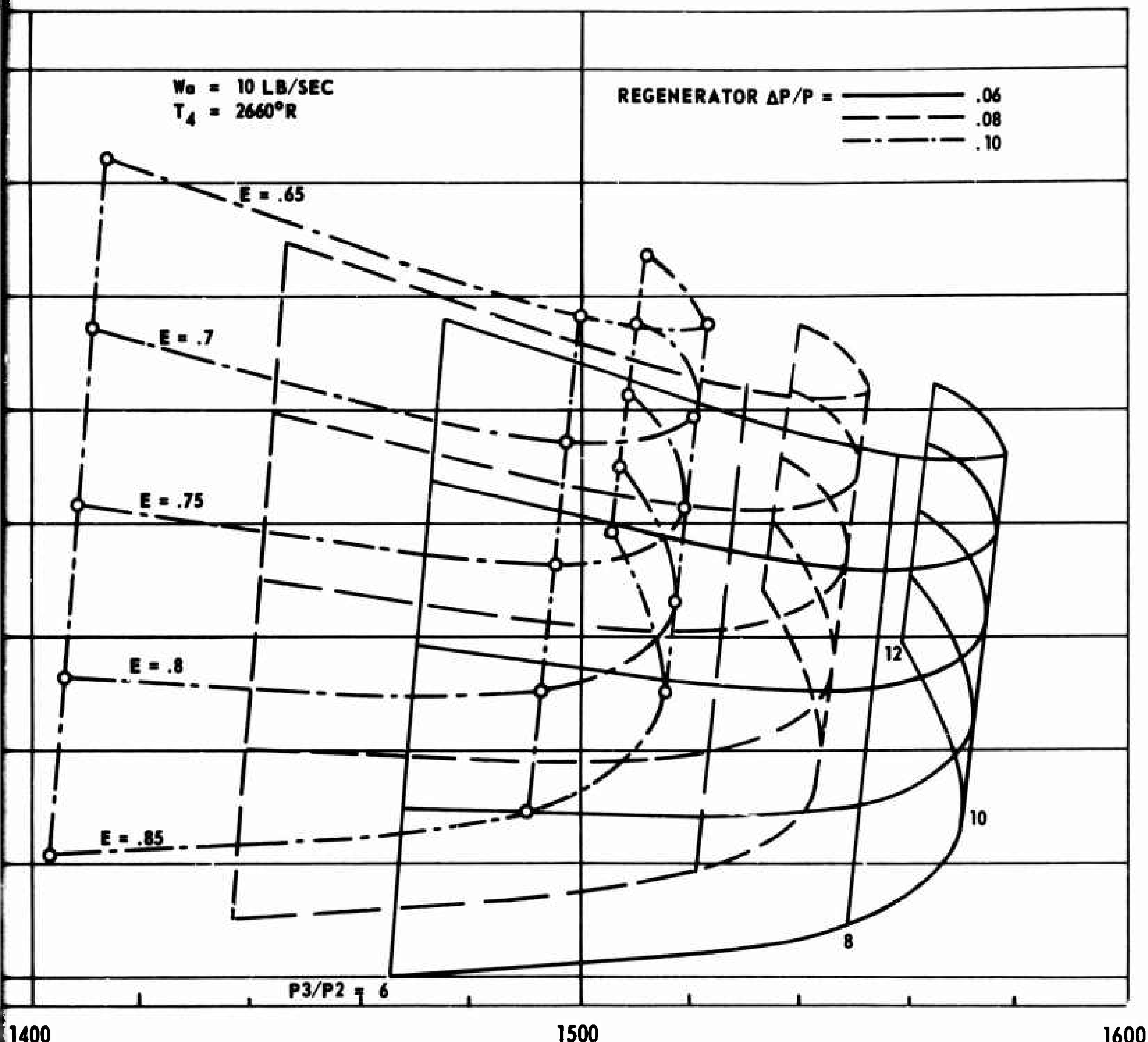


Figure 7. The effect of P3/P2, regenerator ΔP/P & regenerator effectiveness on regenerative engine SHP & BSFC, 6000 feet static, T ambient = 95°F.



7. The effect of P3/P2, regenerator ΔP/P & regenerator effectiveness on regenerative engine SHP & BSFC, 6000 feet static, T ambient = 95°F.

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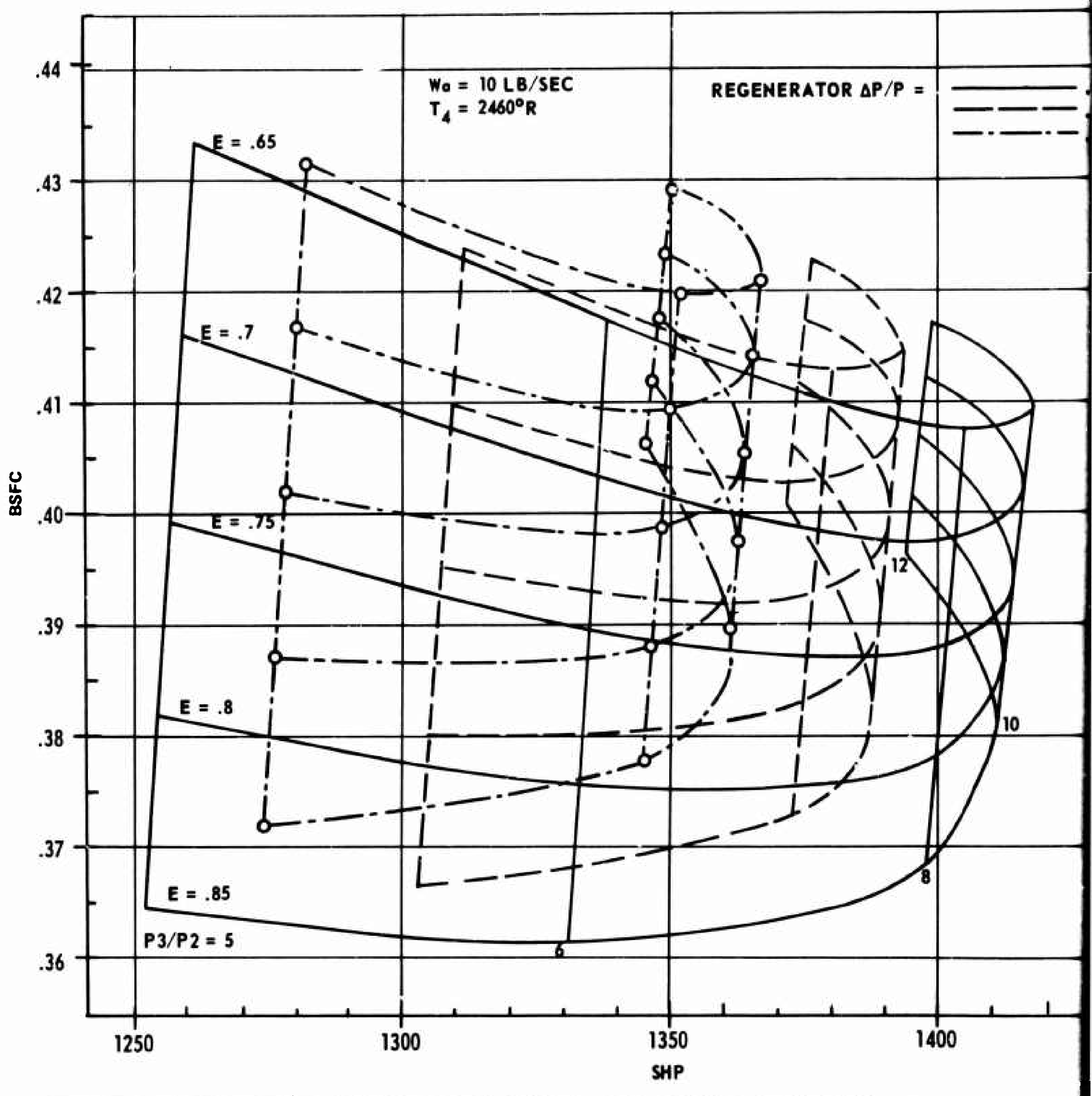

Figure 8. The effect of P3/P2, regenerator ΔP/P & regenerator effectiveness on regenerative engine SHP & BSFC, sea level static, standard day.

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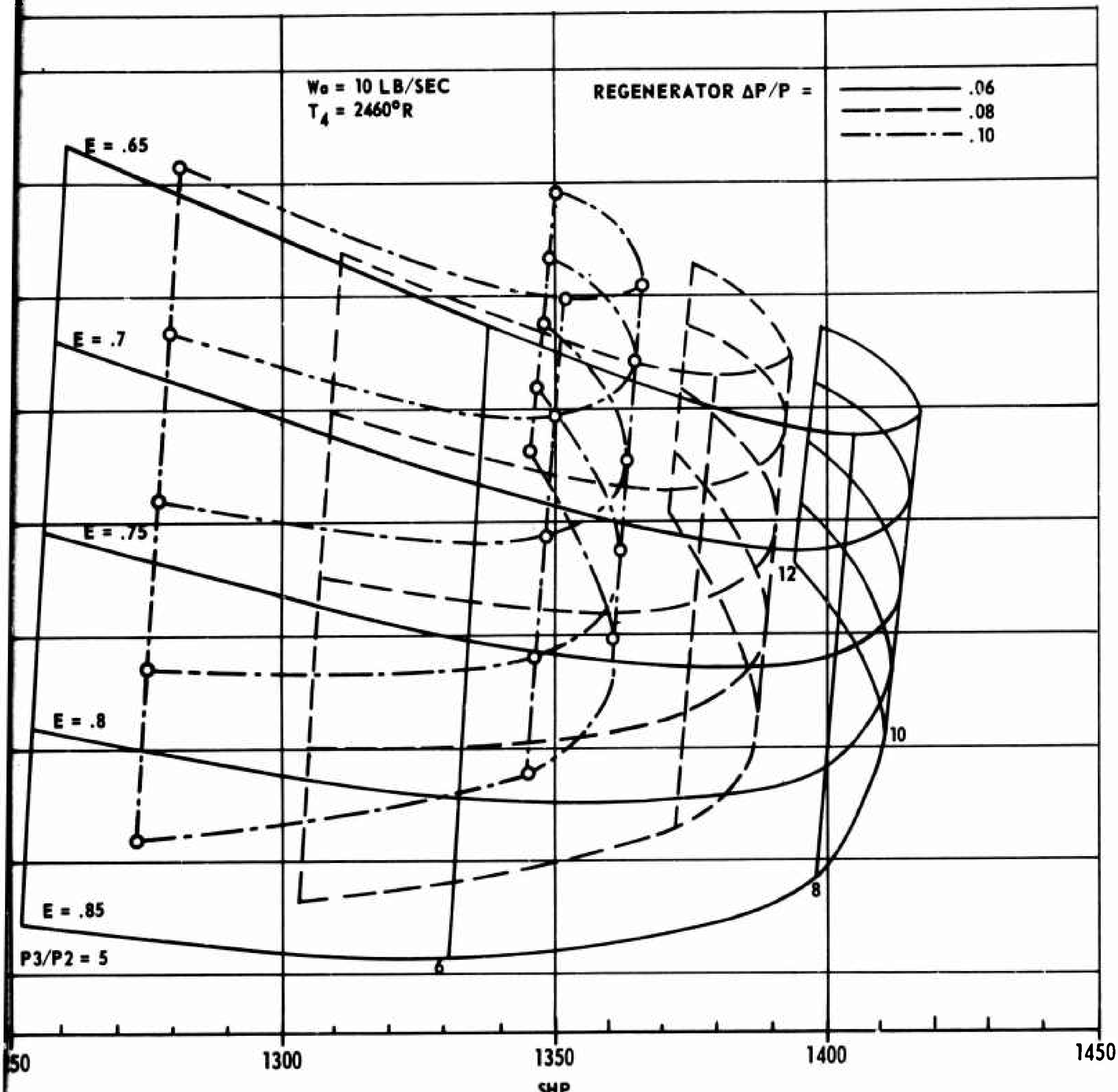

The effect of P3/P2, regenerator ΔP/P & regenerator effectiveness on regenerative engine SHP & BSFC, sea level static, standard day.

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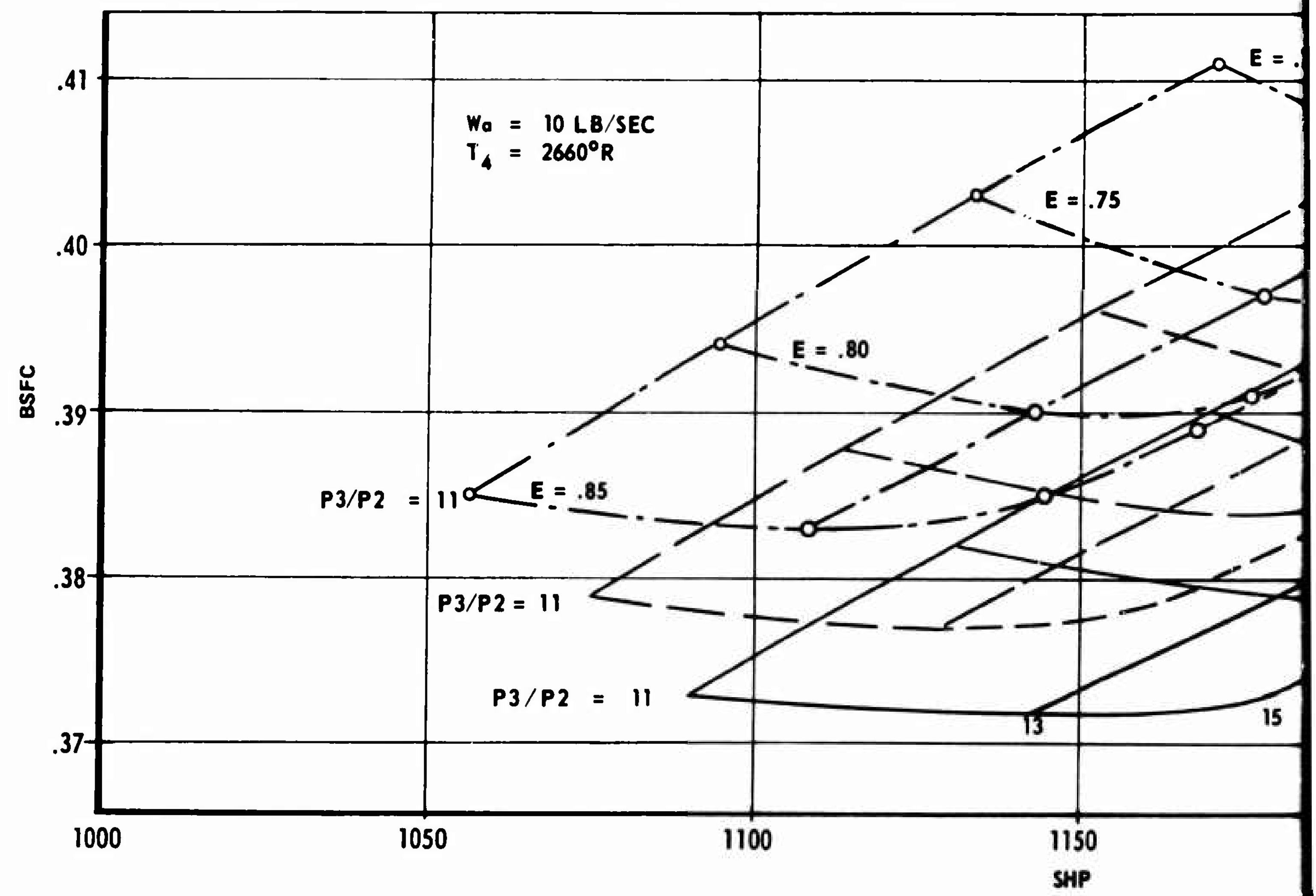
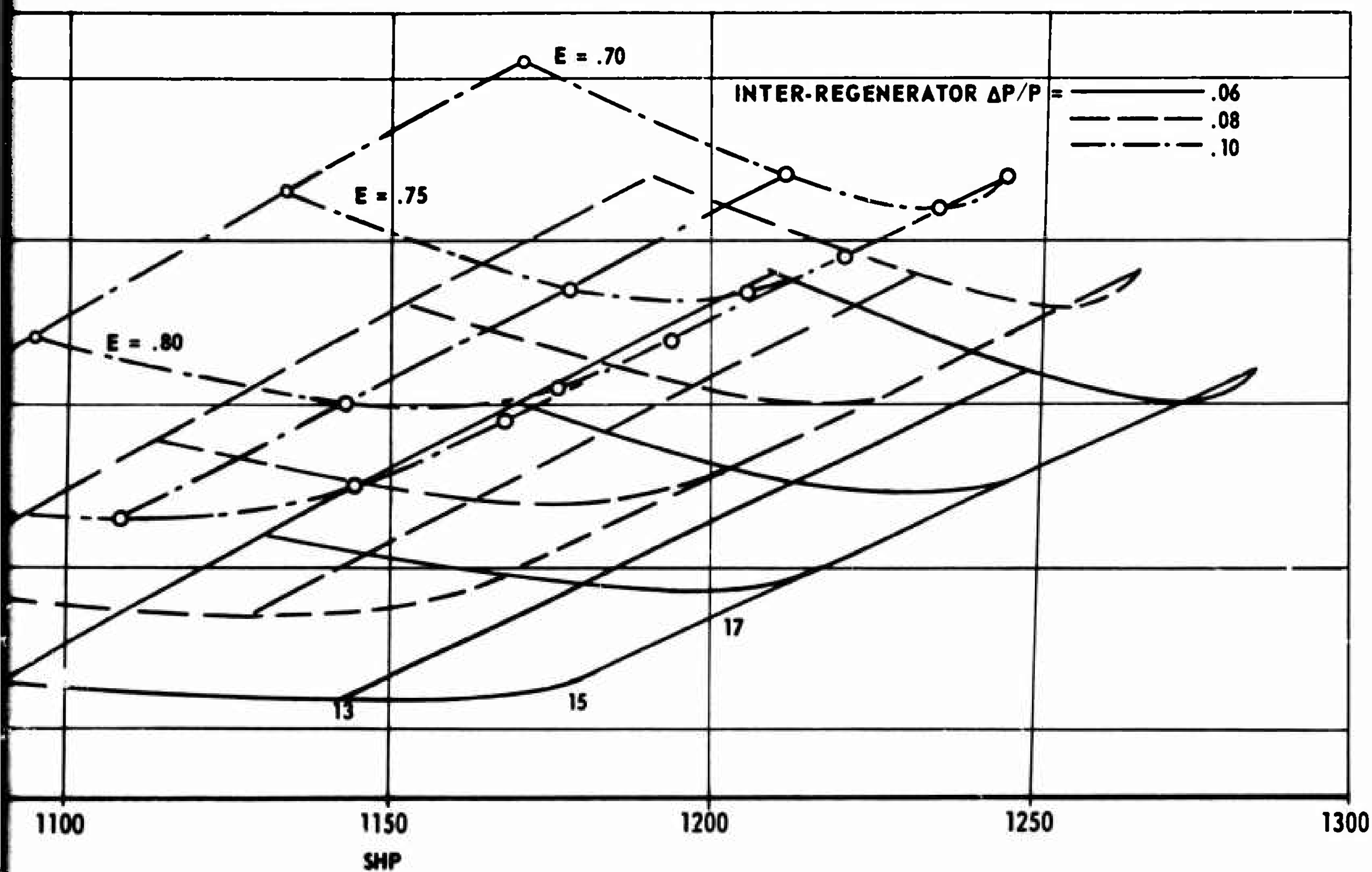


Figure 9. The effect of P3/P2, inter-regenerator $\Delta P/P$ & inter-regenerator effectiveness on inter-regenerative engine SHP & BSFC, sea level static, standard day.



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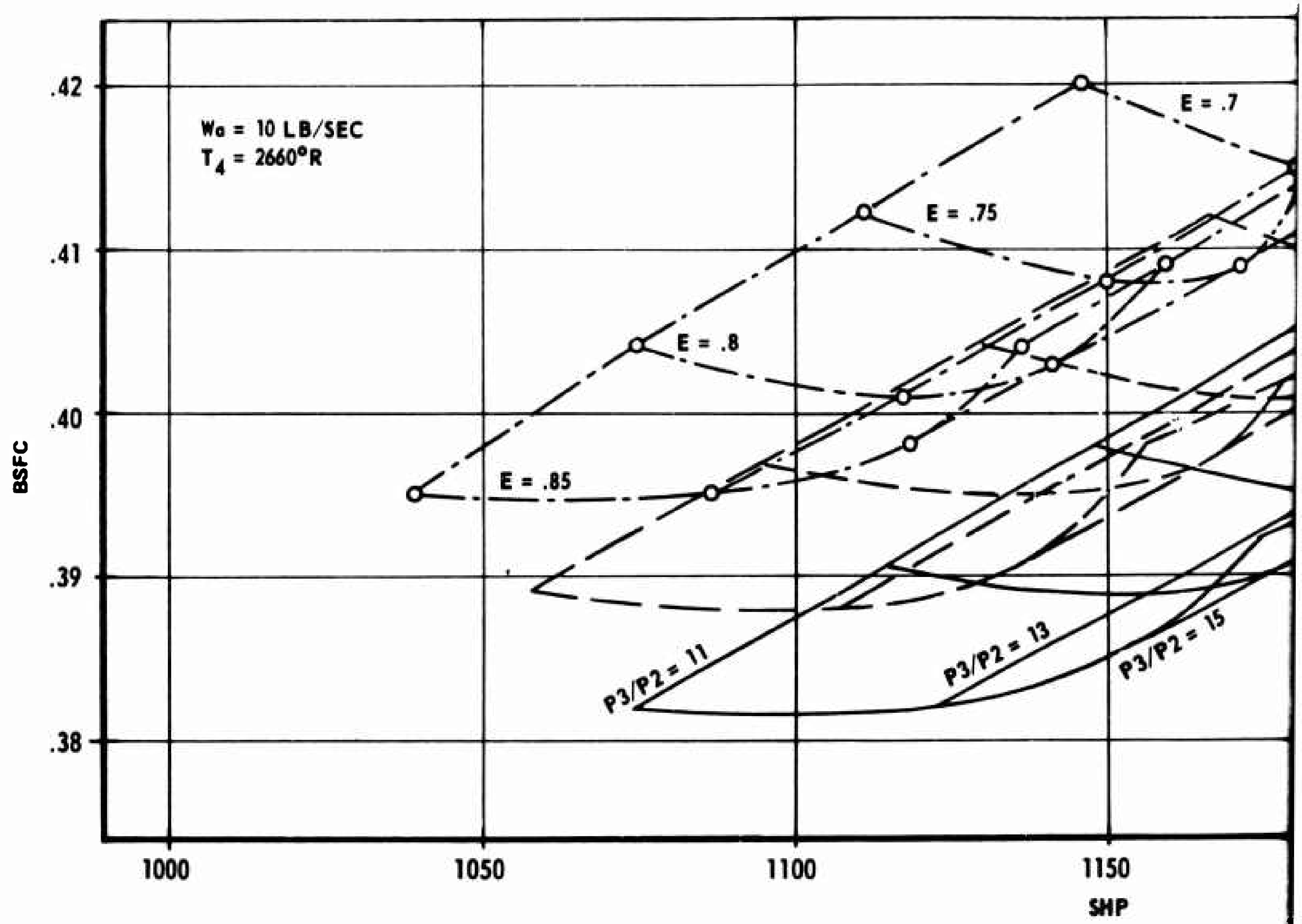
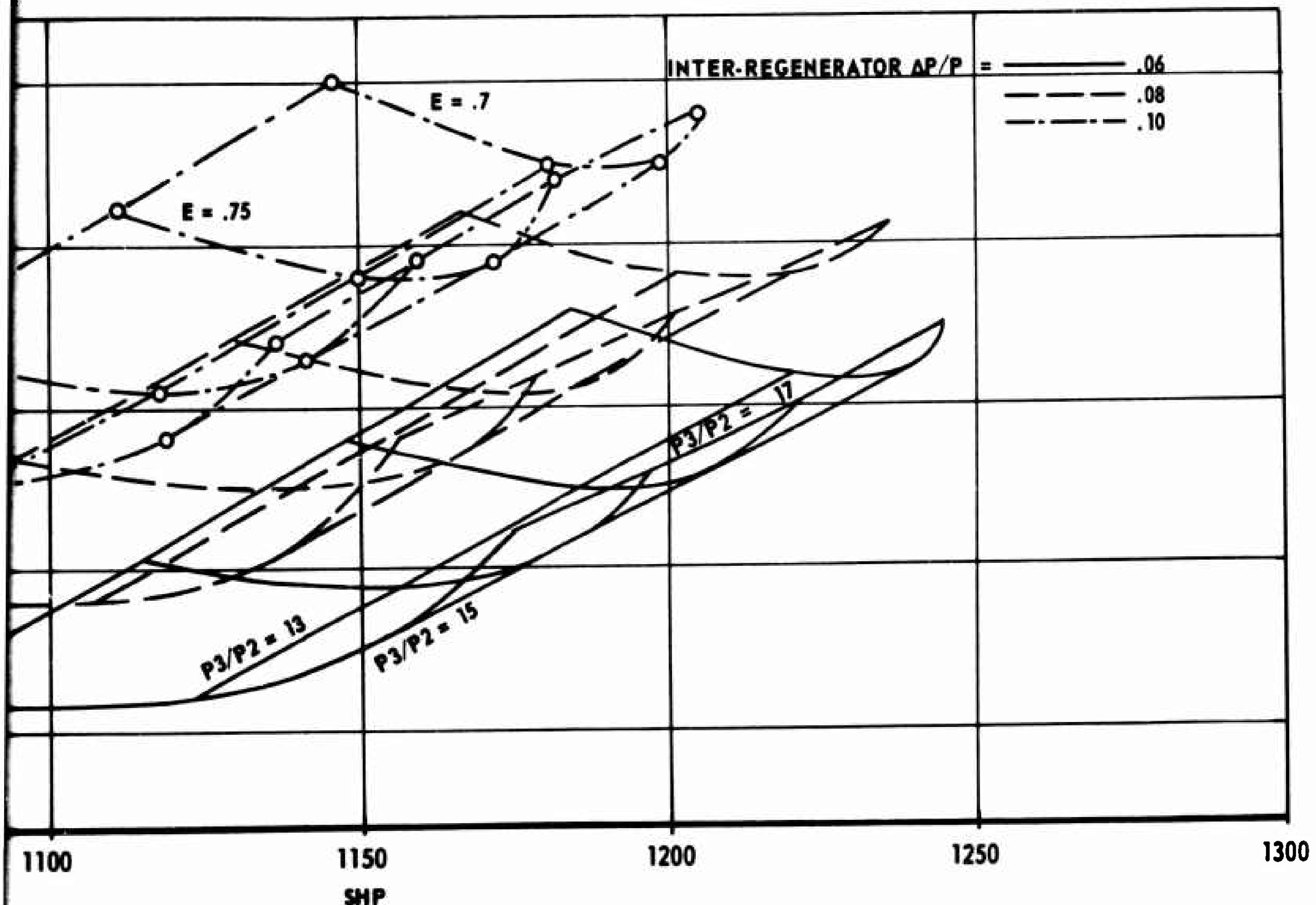


Figure 10. The effect of P3/P2, inter-regenerator ΔP/P & inter-regenerator effectiveness on inter-regenerative engine SHP & BSFC, 3000 feet static, T ambient = 78°F.



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bient = 78°F.

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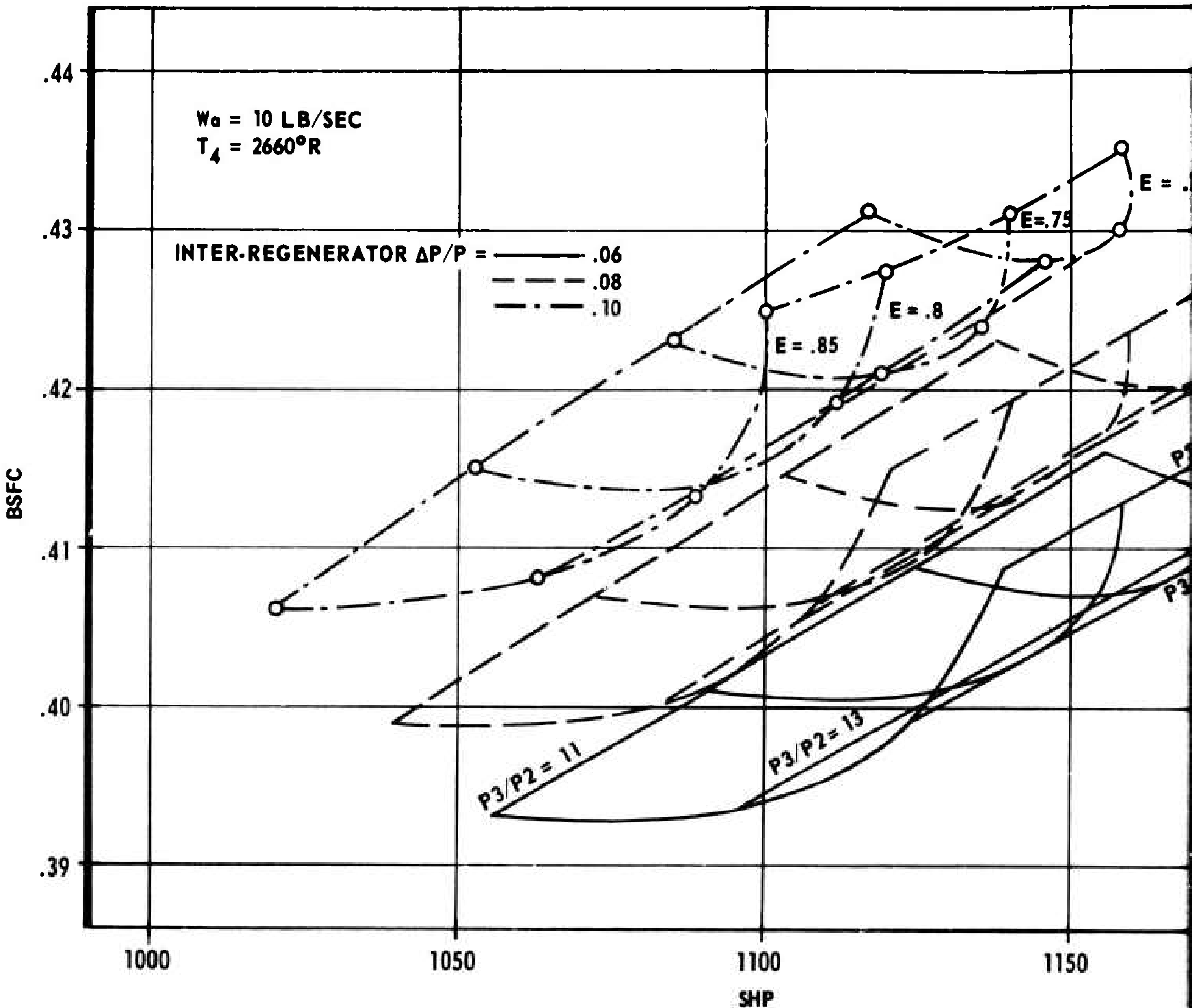

Figure 11. The effect of P3/P2, inter-regenerator ΔP/P & inter-regenerator effectiveness on inter-rege
SHP & BSFC, 6000 feet static, T ambient = 95°F.

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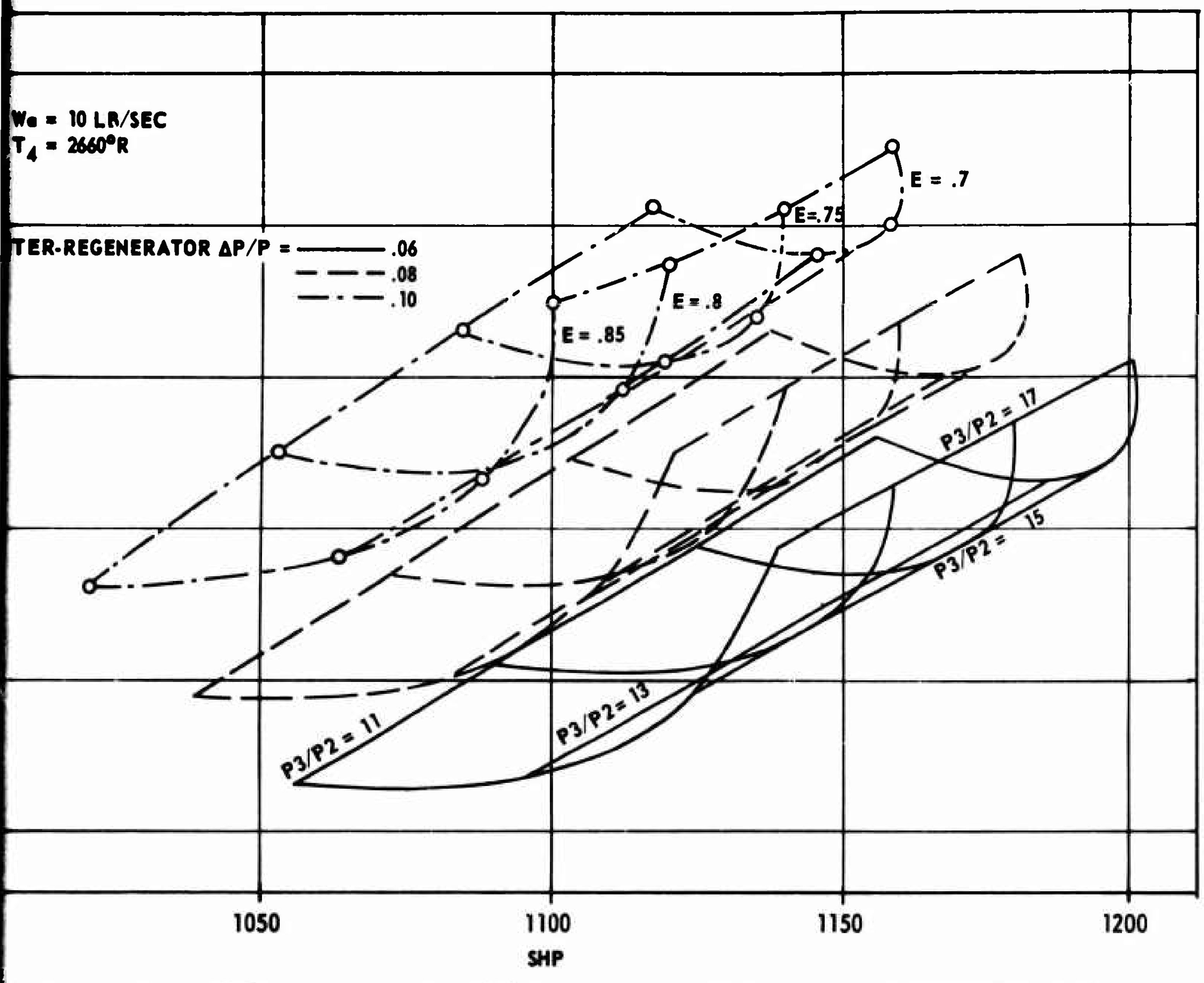

ure 11. The effect of P3/P2, inter-regenerator ΔP/P & inter-regenerator effectiveness on inter-regenerative engine SHP & BSFC, 6000 feet static, T ambient = 95°F.

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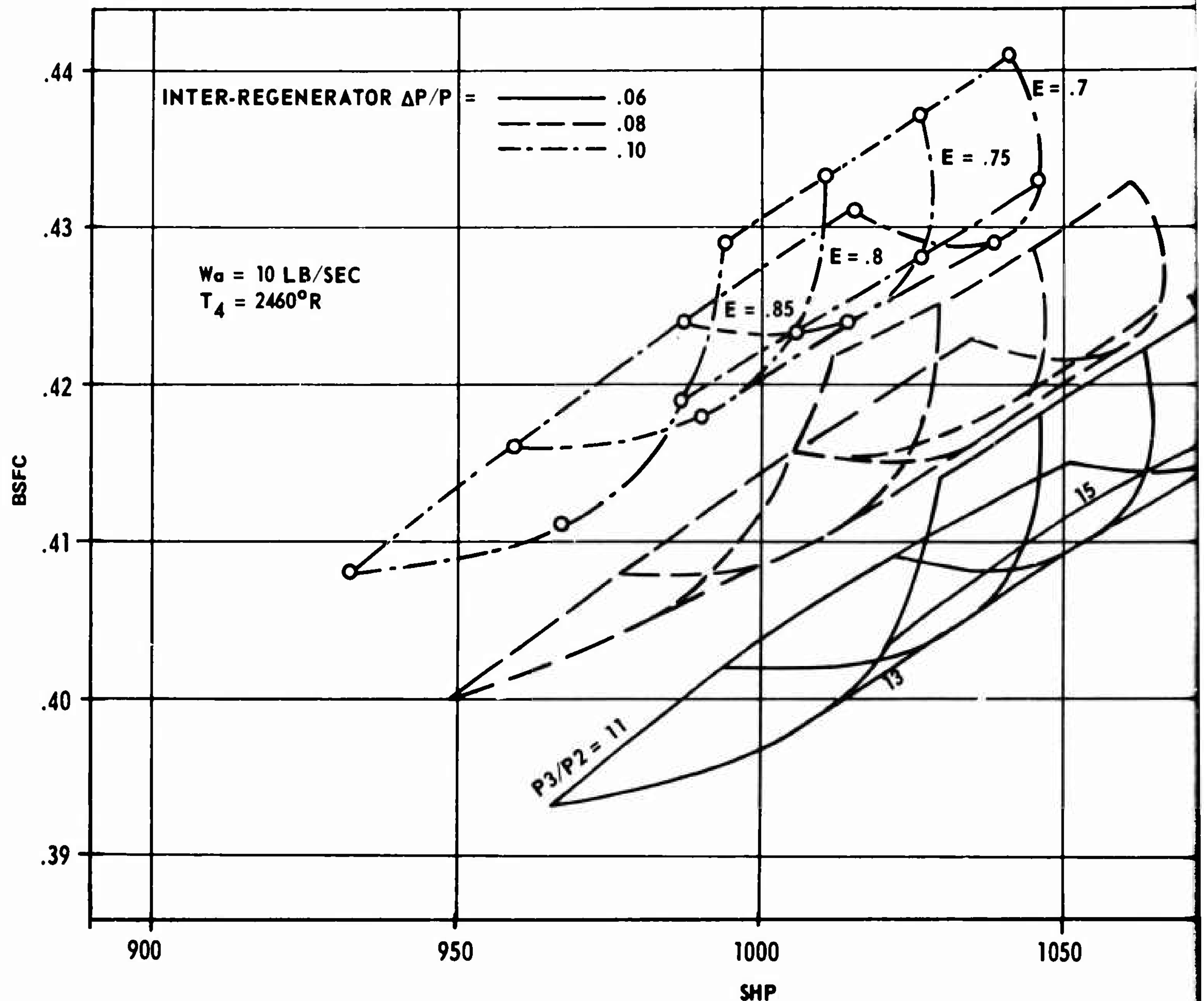
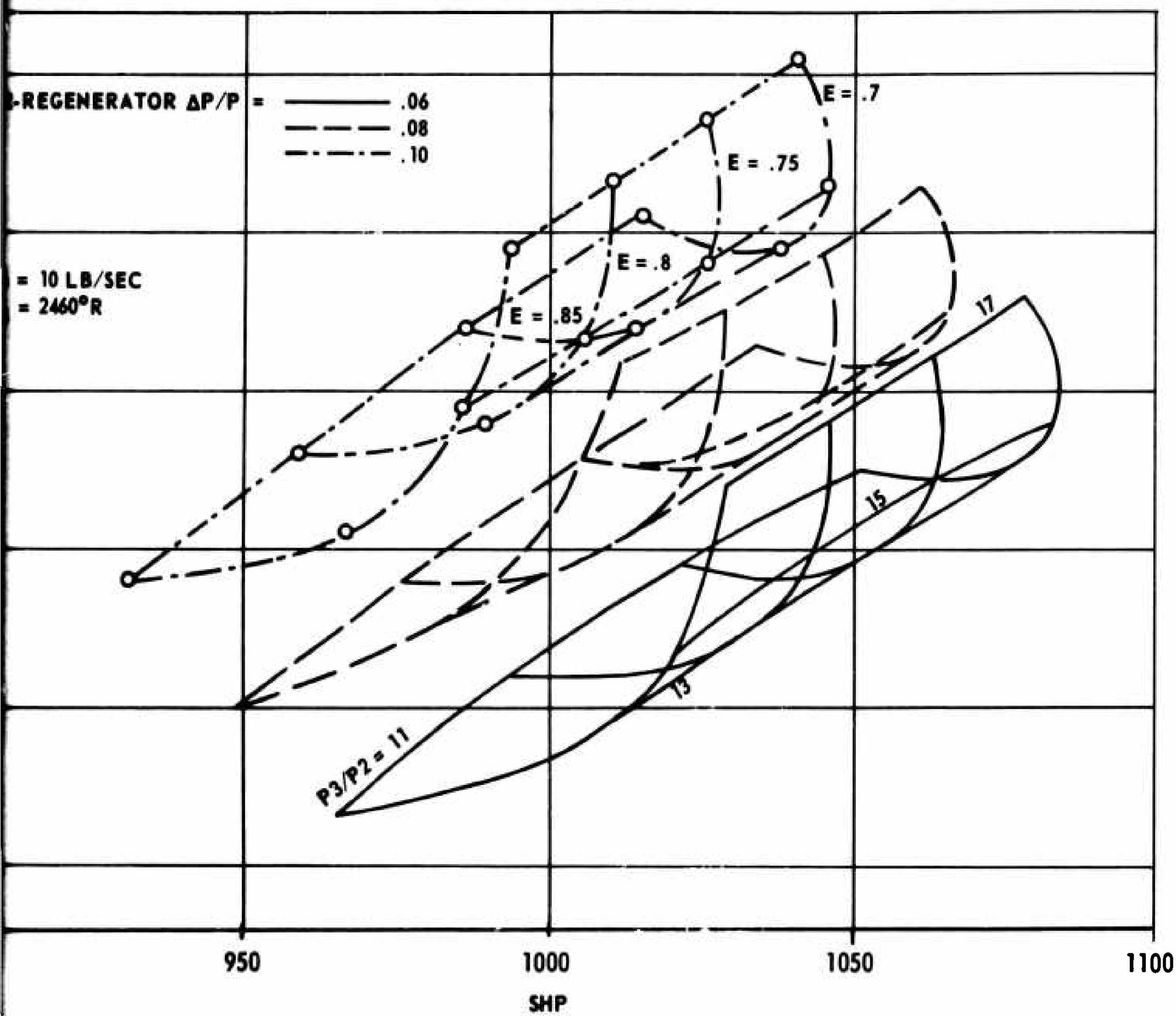


Figure 12. The effect of P3/P2, inter-regenerator ΔP/P & inter-regenerator effectiveness on inter-regenerative SHP & BSFC, sea level static, standard day.



The effect of P3/P2, inter-regenerator ΔP/P & inter-regenerator effectiveness on inter-regenerative engine SHP & BSFC, sea level static, standard day.

B

TABLE III

THERMODYNAMIC DESIGN VALUES OF BASIC ENGINES

Engine Type	Design Point	P_3/P_2	η_c	Wa Lb/Sec	$\frac{W\sqrt{\theta}}{\delta}$	T_4	Guar Level SHP	Guar Level BSFC	ε	$\frac{\Delta P}{P}$	WL_3
Non-Regenerative Turboshaft	SL Static	17	.8275	10	10	2200°F	1704	.426	-	-	-
Non-Regenerative Turboshaft	3000 Ft Static 78°F	16.42	.828	-	11.23	-	1643	.441	-	-	-
Non-Regenerative Turboshaft	6000 Ft Static 95°F	15.925	.829	-	12.67	-	1560	.452	-	-	-
Inter-Turbine Regenerative Turboshaft	SL Static 60°F	13	.833	-	10	-	1202	.404	.75	.08	-
Inter-Turbine Regenerative Turboshaft	3000 Ft Static 78°F	12.56	.8335	-	11.23	-	1163	.417	.75	-	-
Inter-Turbine Regenerative Turboshaft	6000 Ft Static 95°F	12.18	.834	-	12.67	-	1131	.427	.75	-	-
Post-Turbine Regenerative Turboshaft	SL Static 60°F	9	.84	-	10	-	1520	.375	.89	-	3%
Post-Turbine Regenerative Turboshaft	3000 Ft Static 78°F	8.7	.8405	-	11.23	-	1453	.387	.89	-	3%
Post-Turbine Regenerative Turboshaft	6000 Ft Static 95°F	8.43	.841	26	12.67	-	1365	.397	.89	-	3%

TABLE IV

BASIC ENGINE MECHANICAL DESIGN FEATURES

Engine Type	Non-Regenerative Turboshaft	Inter-Turbine Regenerative Turboshaft	Post-Turbine Regenerative Turboshaft
Compressor	Axial Centrifugal Twin Rotor - L. P. Rotor 5 Axial Stages - H. P. Rotor 3 Axial and 1 Centrifugal Stage	Single-Shaft Axial Centrifugal With 7 Axial and 1 Centrifugal Stage	Single-Shaft Axial Centrifugal With 3 Axial and 1 Centrifugal Stage
Combustor	Single Annular With Fuel Slinger	Single Annular With Fuel Slinger	Single Annular With Spray Nozzle
Gas Generator Turbine	High Pressure and Low Pressure Each Cooled Single Stage	2-Stage Air Cooled	2-Stage Air Cooled
Power Turbine	2-Stage Uncooled 25,000 RPM Free Shaft. Offset Parallel Axis	2-Stage Uncooled 25,000 RPM Free Shaft	2-Stage Uncooled 25,000 RPM Free Shaft With Variable Inlet Nozzle
Regenerator		Stationary Cross-Counter Flow Located Between Turbines With Full Bypass for Both Gas and Air Sides	25 RPM Rotary Counterflow Driven From Power Turbine Through 1000 to 1 Reduction Ratio Harmonic Drive. Partial Bypass Air and Gas Side
Remarks	End Location of Accessories and Combustor for Ease of Accessibility and Hot Part Inspection	Full Bypass Arrangement for Minimum Losses and Maximum Power When Bypassing	Cruciform Shaft Arrangement Simplifies Ducting, Reduces Losses, and Provides Power Take-Off, Front and Rear
	Offset Parallel Shaft Arrangement to Provide Power Take-Off, Front and Rear		Split Ducts to Regenerator Minimizes Unbalance Press Forces
	Inverted Compressor Turbine Arrangement Permit Small Diameter for High-Speed Shaft for Relief in Bearing Design Requirements		End Location of Accessories and Combustor for Ease of Accessibility and Hot Part Inspection
			Variable Geometry Turbine for Optimum Performance

TABLE V

BASIC ENGINE WEIGHTS AND ENVELOPE DIMENSIONS

Engine Type	Design Point	Weight (Pounds)	Length (Inches)	Width (Inches)	Height (Inches)
Non-Regenerative Turboshaft	SL Static 60°F	290	42	21	34
Non-Regenerative Turboshaft	3000 Ft Static 78°F	330	45	22	36
Non-Regenerative Turboshaft	6000 Ft Static 95°F	380	47	24	38
Inter-Turbine Regenerative Turboshaft	SL Static 60°F	720	86	36	38
Inter-Turbine Regenerative Turboshaft	3000 Ft Static 78°F	825	90	38	41
Inter-Turbine Regenerative Turboshaft	6000 Ft Static 95°F	940	96	41	43
Post-Turbine Regenerative Turboshaft	SL Static 60°F	905	46	32	44
Post-Turbine Regenerative Turboshaft	3000 Ft Static 78°F	1040	49	34	47
Post-Turbine Regenerative Turboshaft	6000 Ft Static 95°F	1178	52	36	50

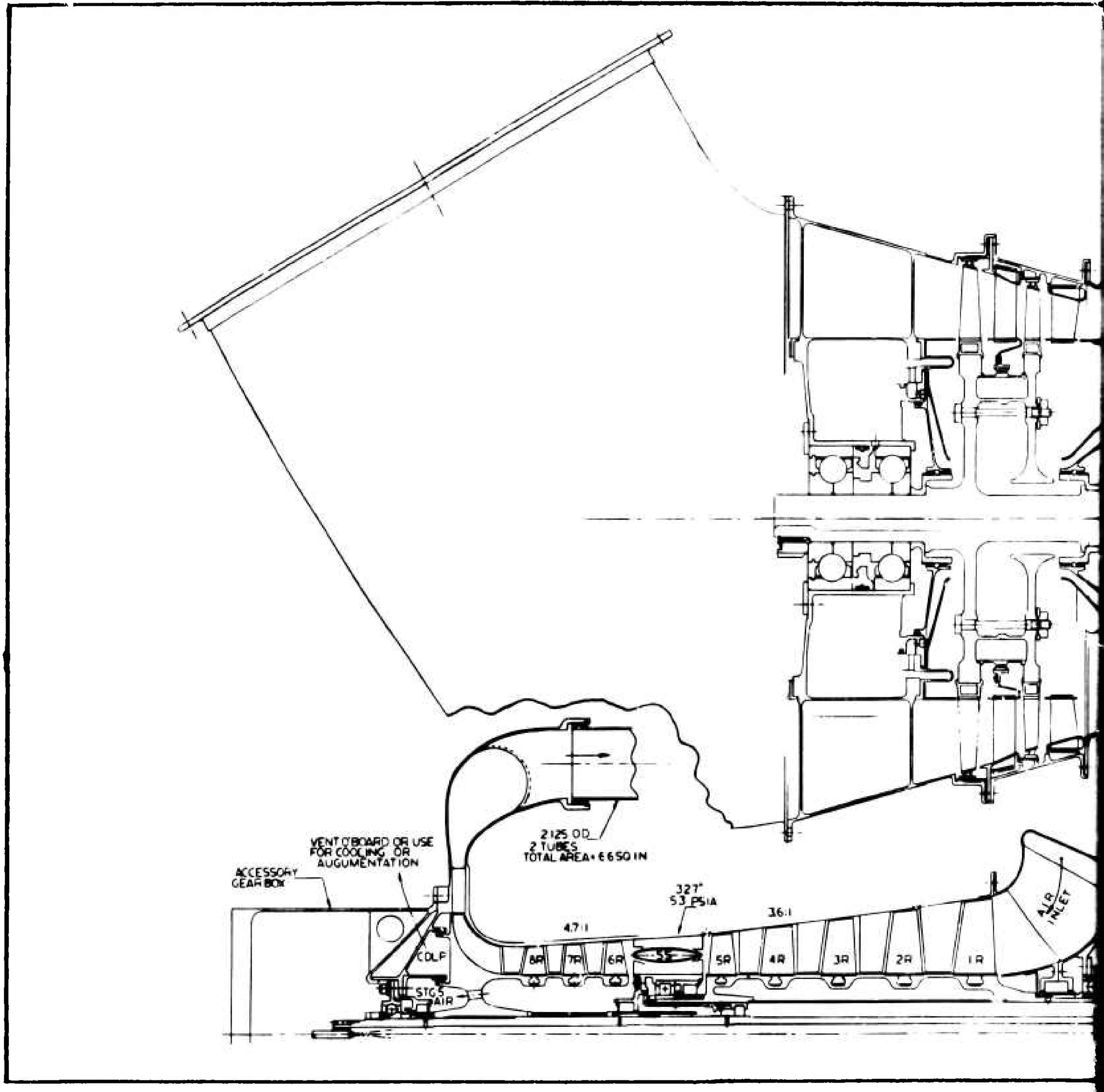
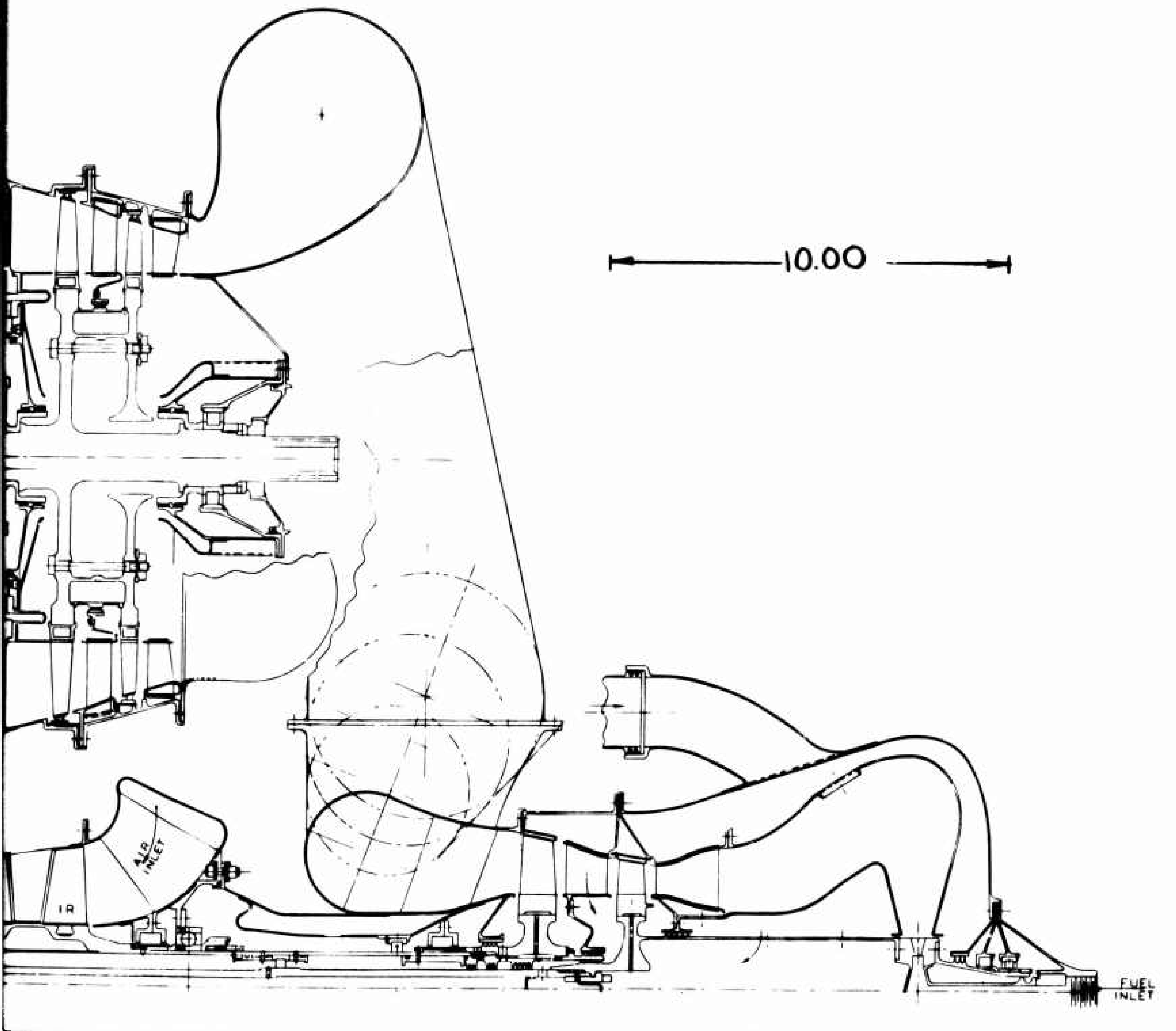


Figure 13. Typical non-regenerative engine arranged with the compressor inlet between the compressor and turbine, end mounting of the combustor and accessories and the power turbine on an offset parallel axis shaft.



B

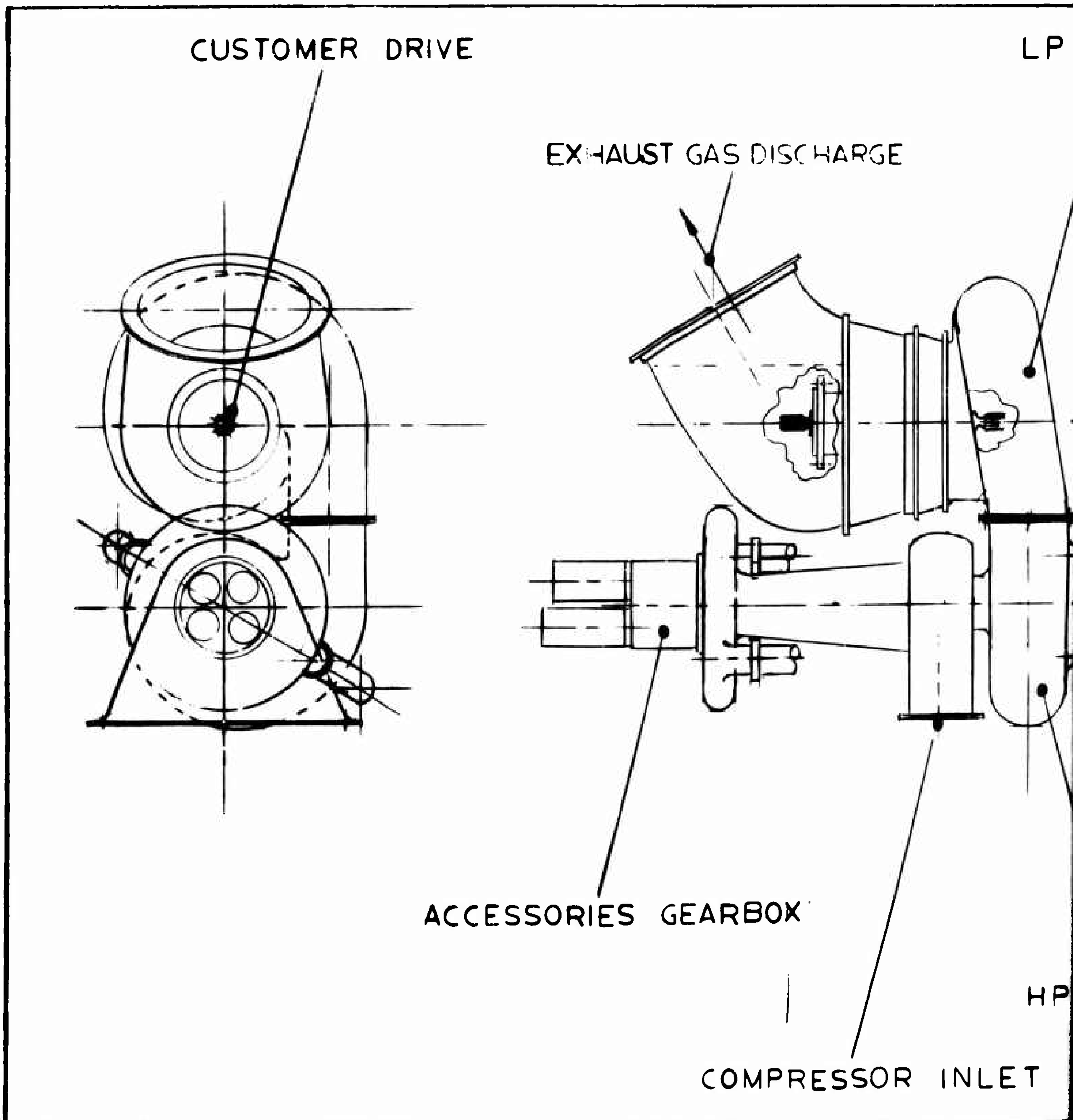
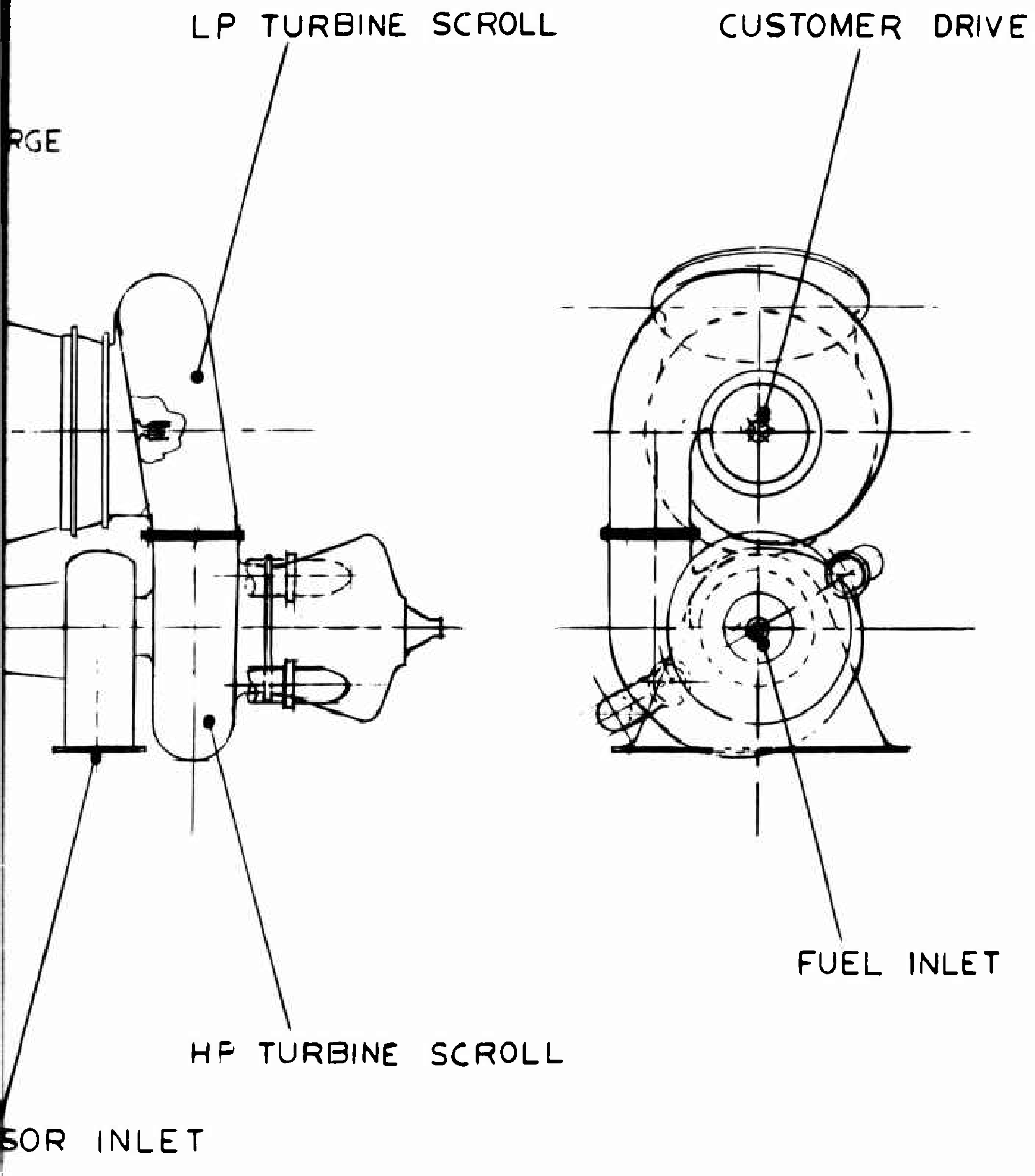


Figure 14. Typical non-regenerative engine.



LP TURBINE SCROLL
CUSTOMER DRIVE
RGE
FUEL INLET
HP TURBINE SCROLL
SOR INLET

B

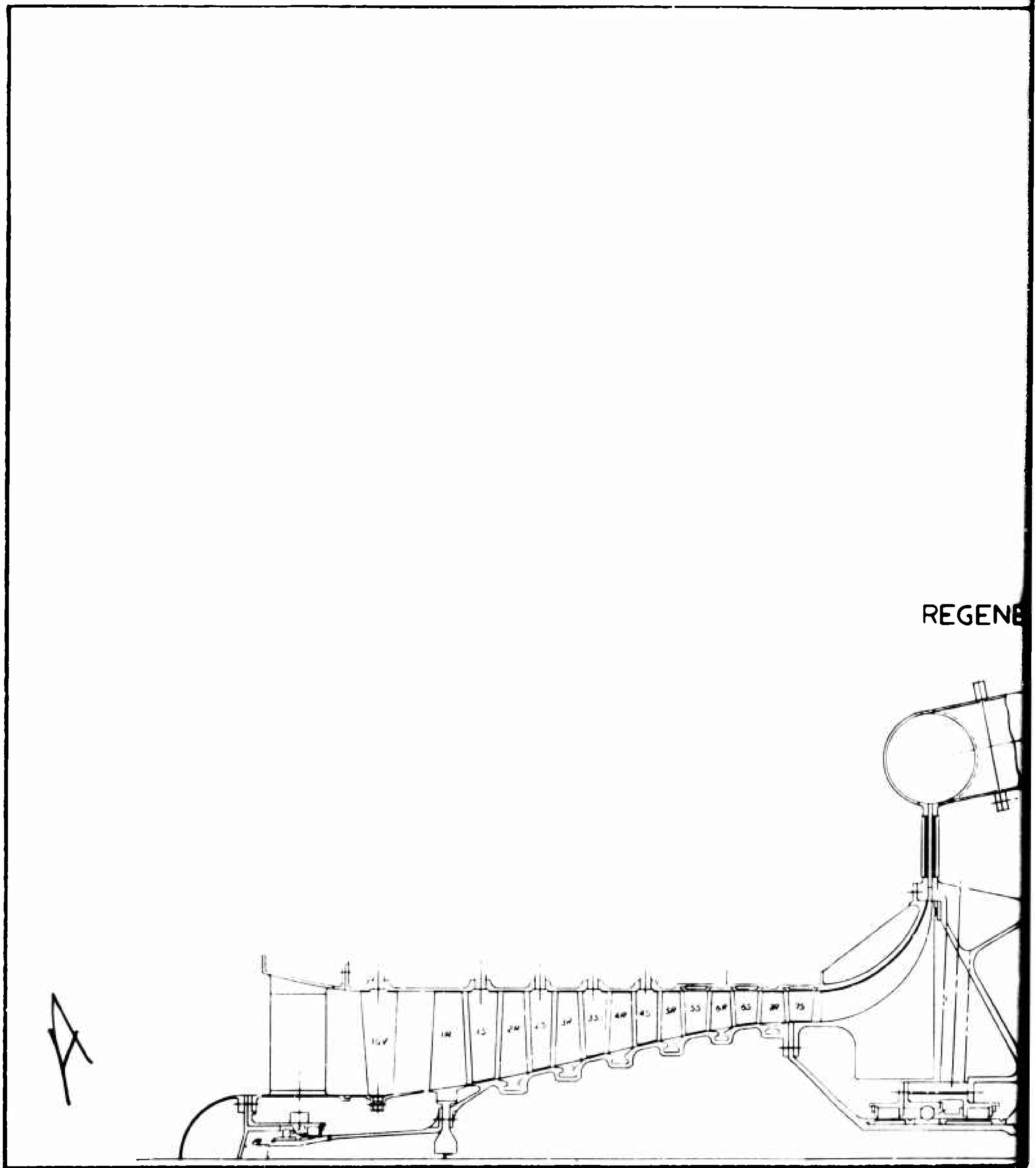
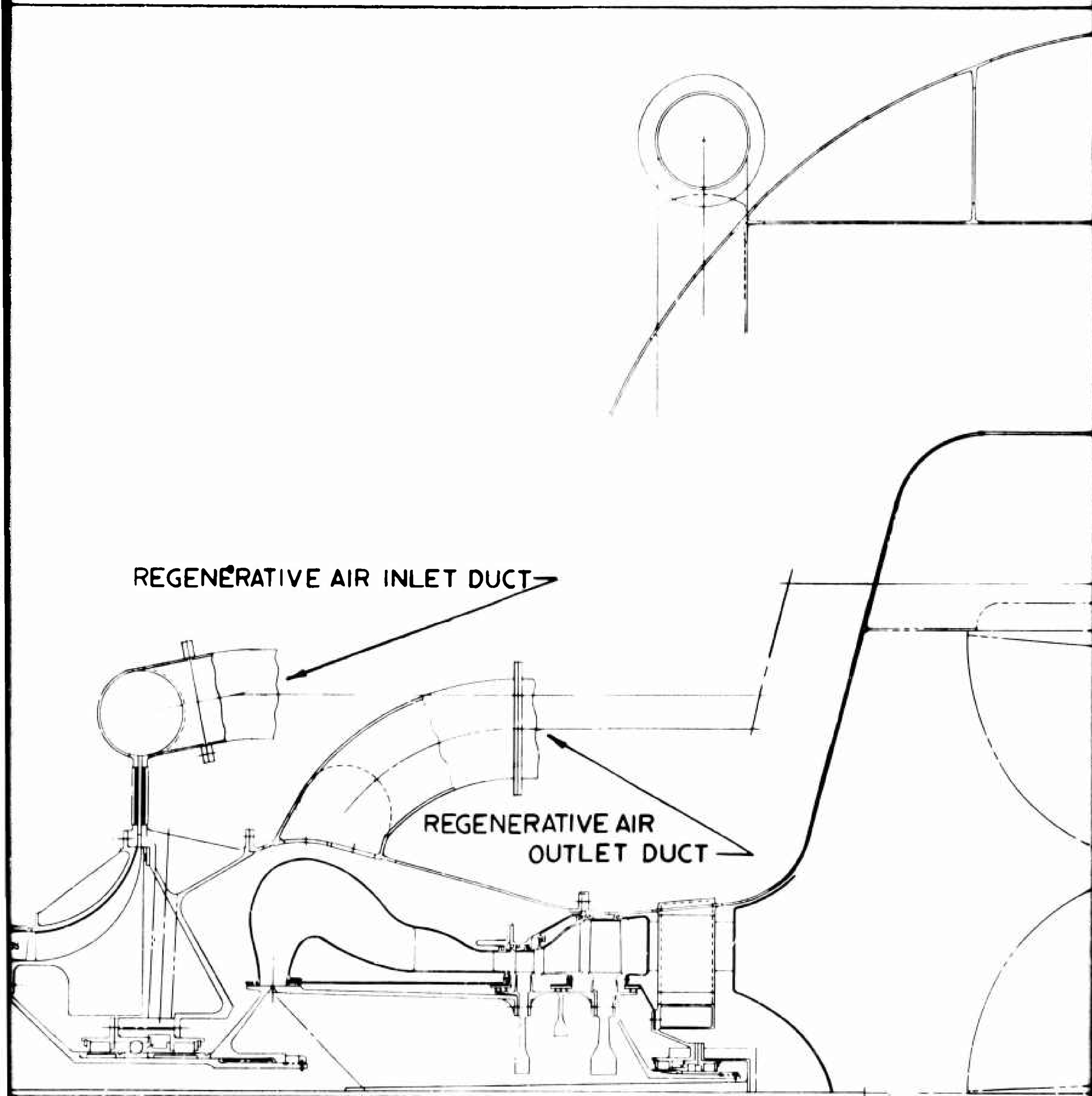


Figure 15. Typical inter-turbine regenerative engine conventionally arranged with co-axial shafts and single pass cross-counterflow static regenerator located between the compressor turbine and power turbine.



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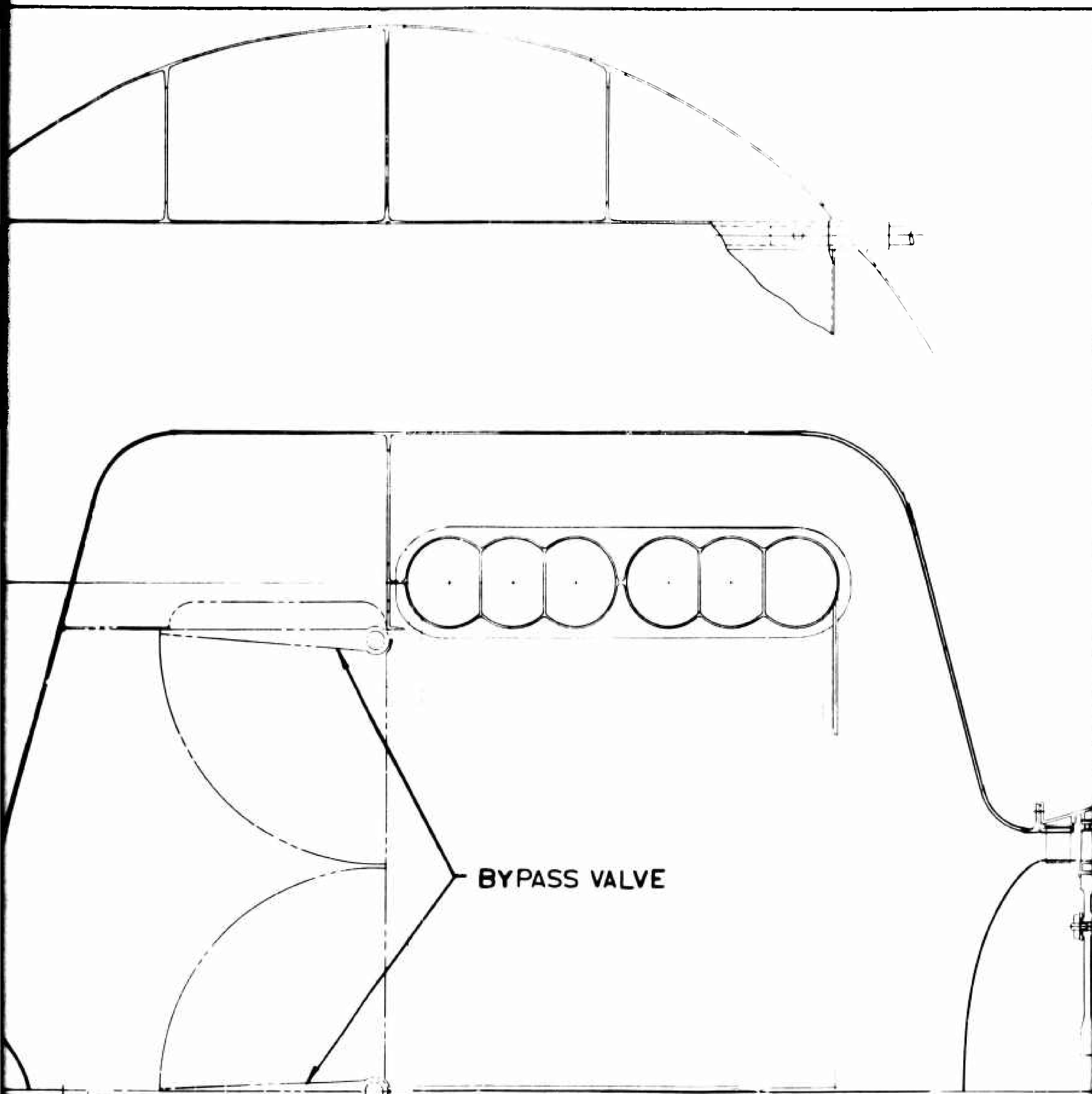
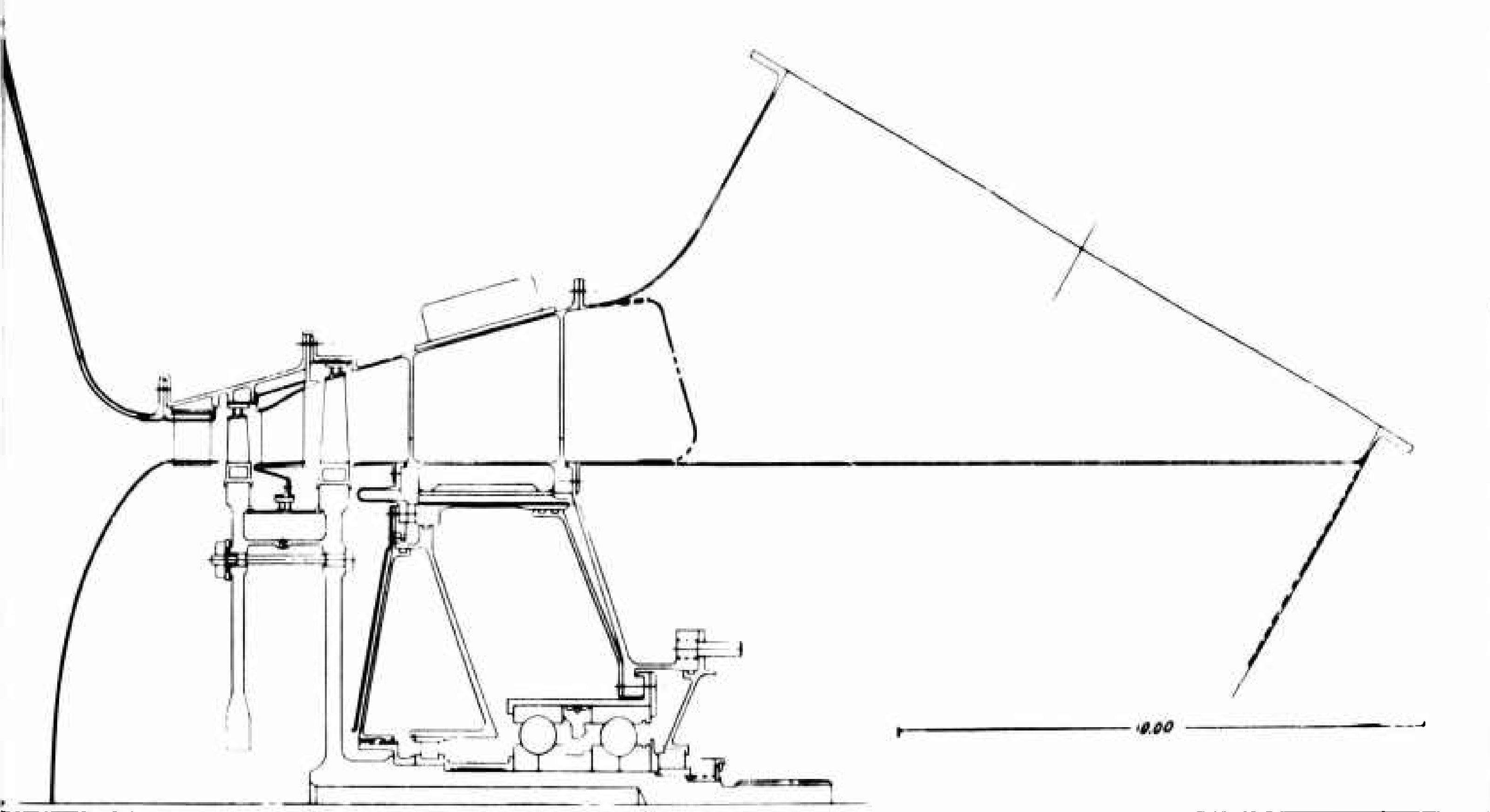

BYPASS VALVE



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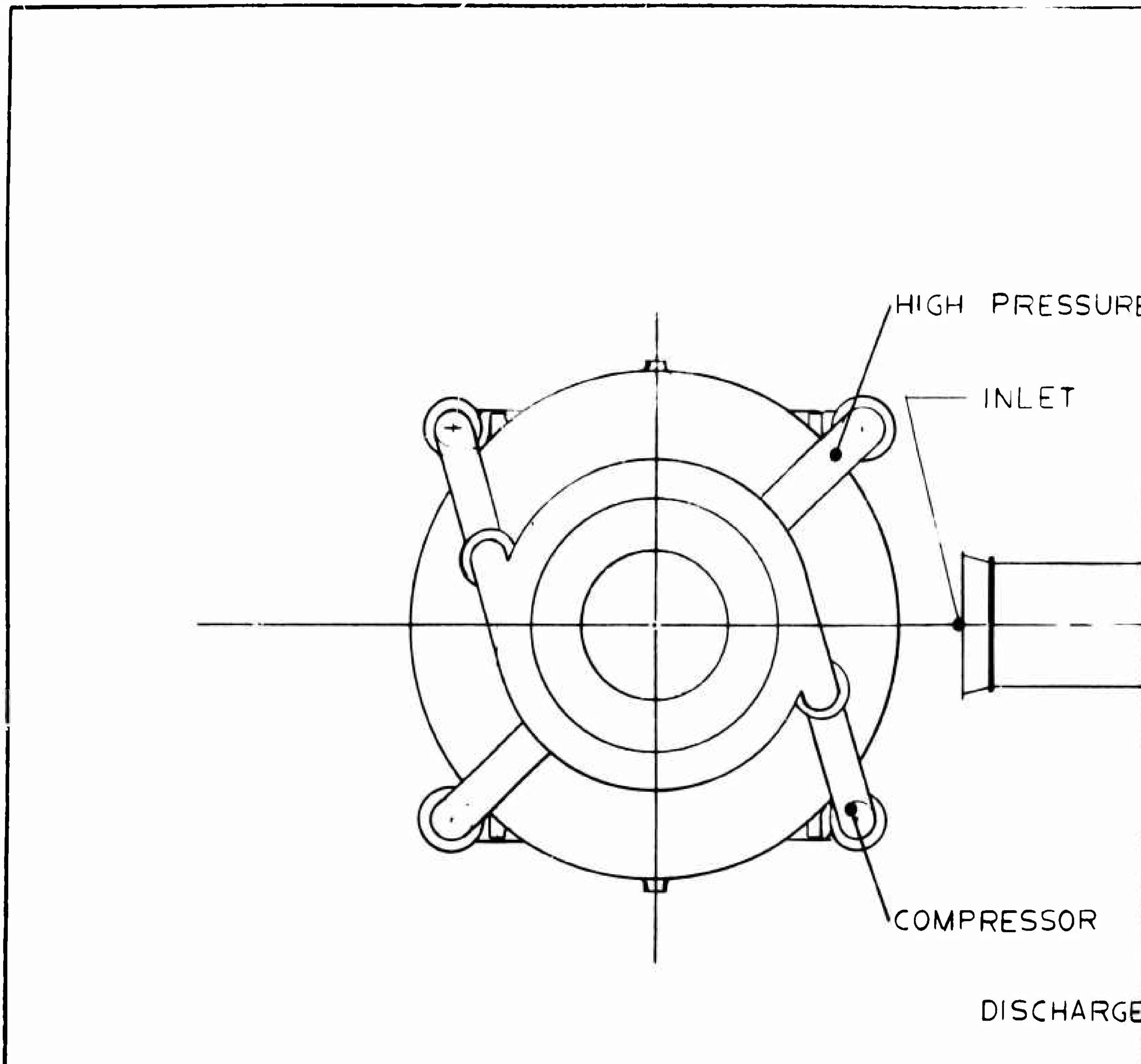
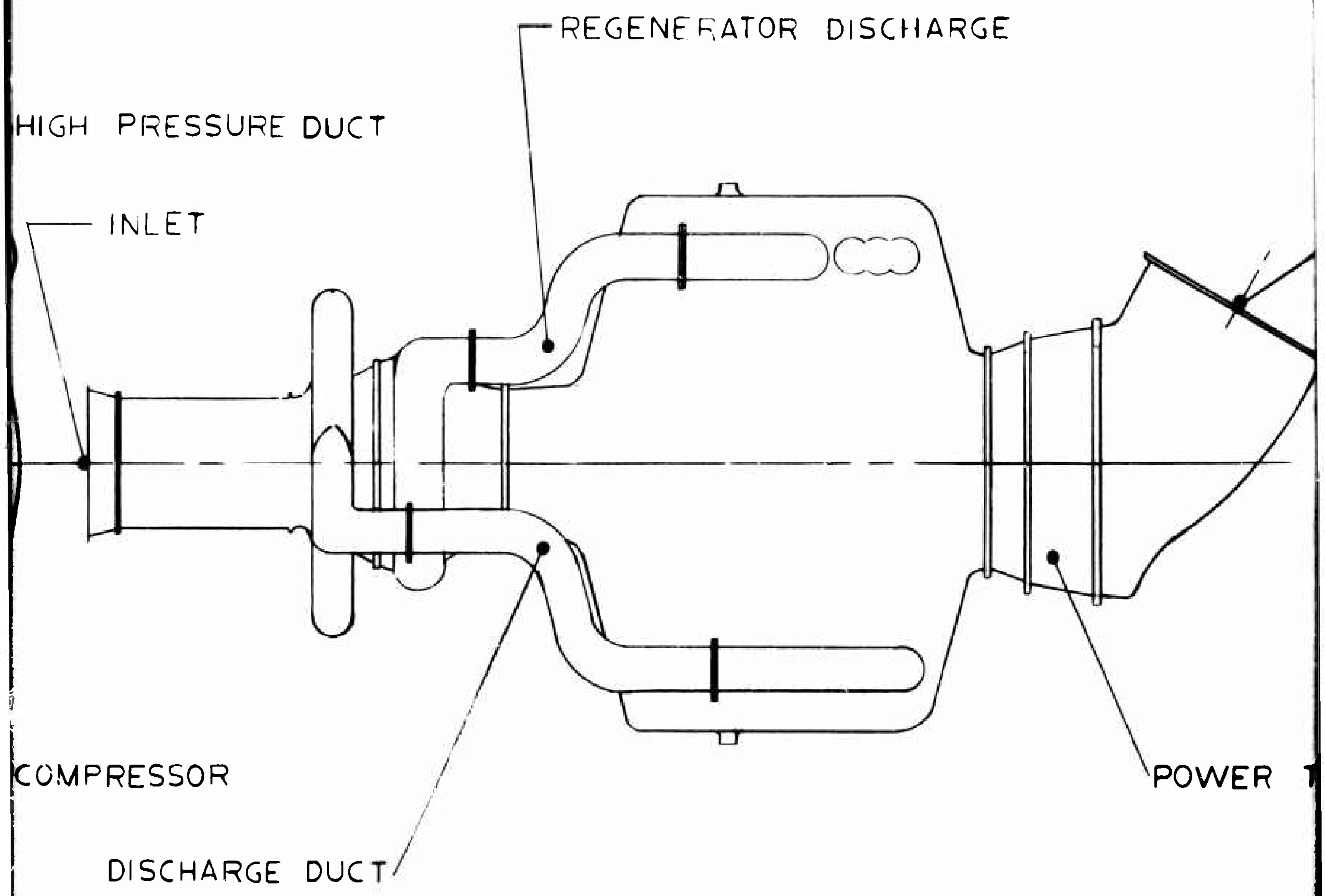
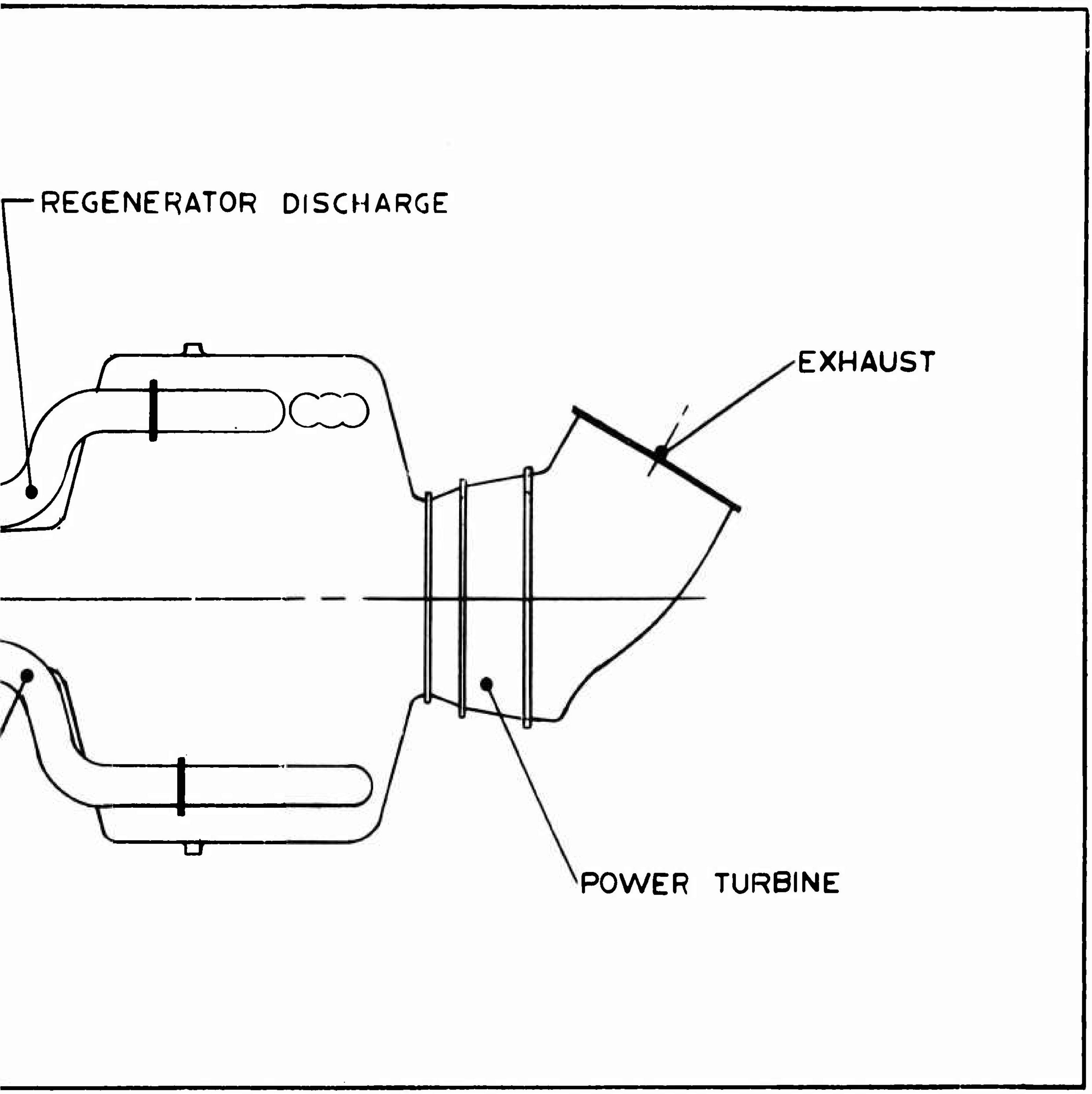


Figure 16. Typical inter-turbine regenerative engine.


REGENERATOR DISCHARGE
HIGH PRESSURE DUCT
INLET
COMPRESSOR
DISCHARGE DUCT
POWER T

B



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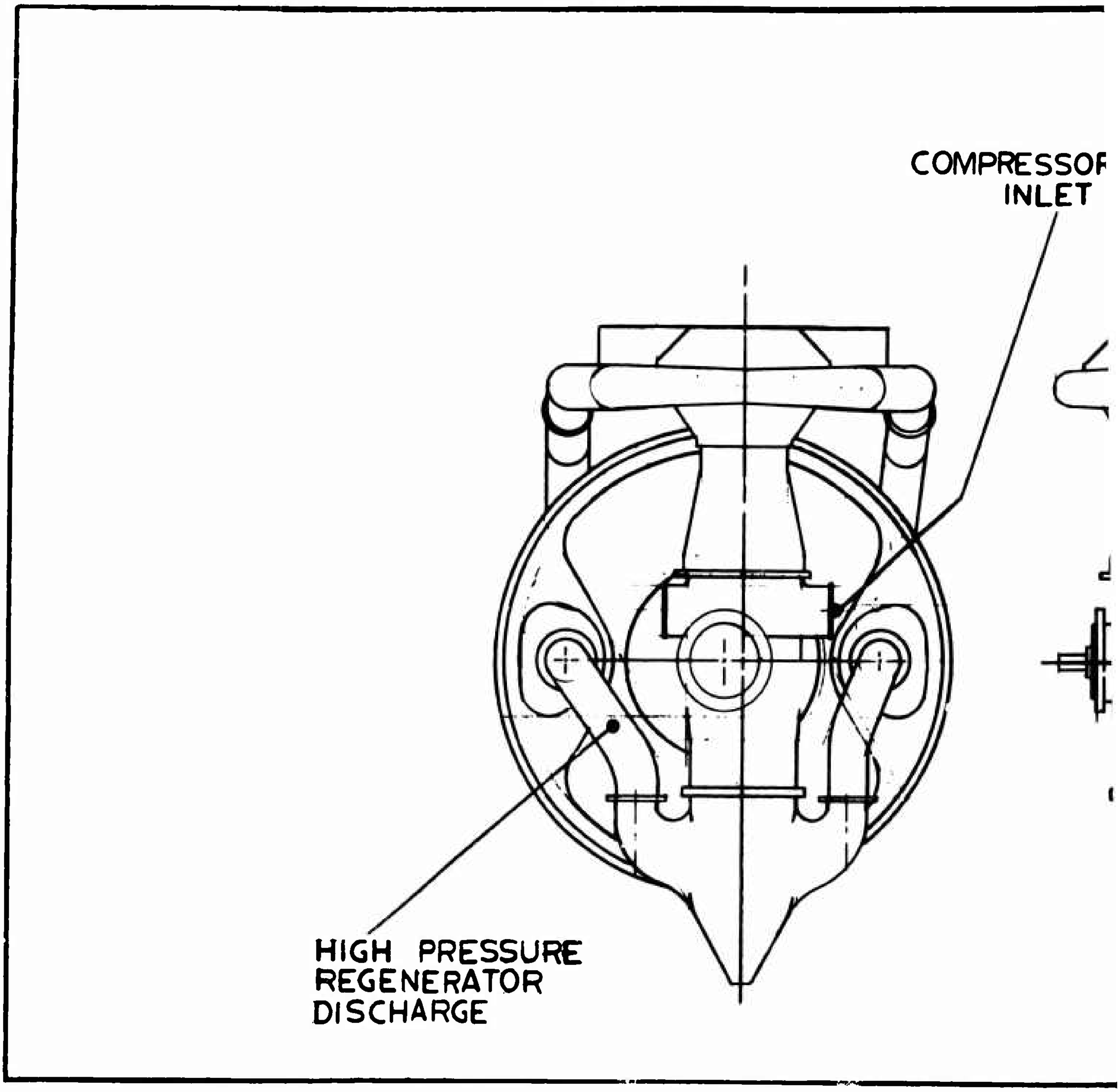
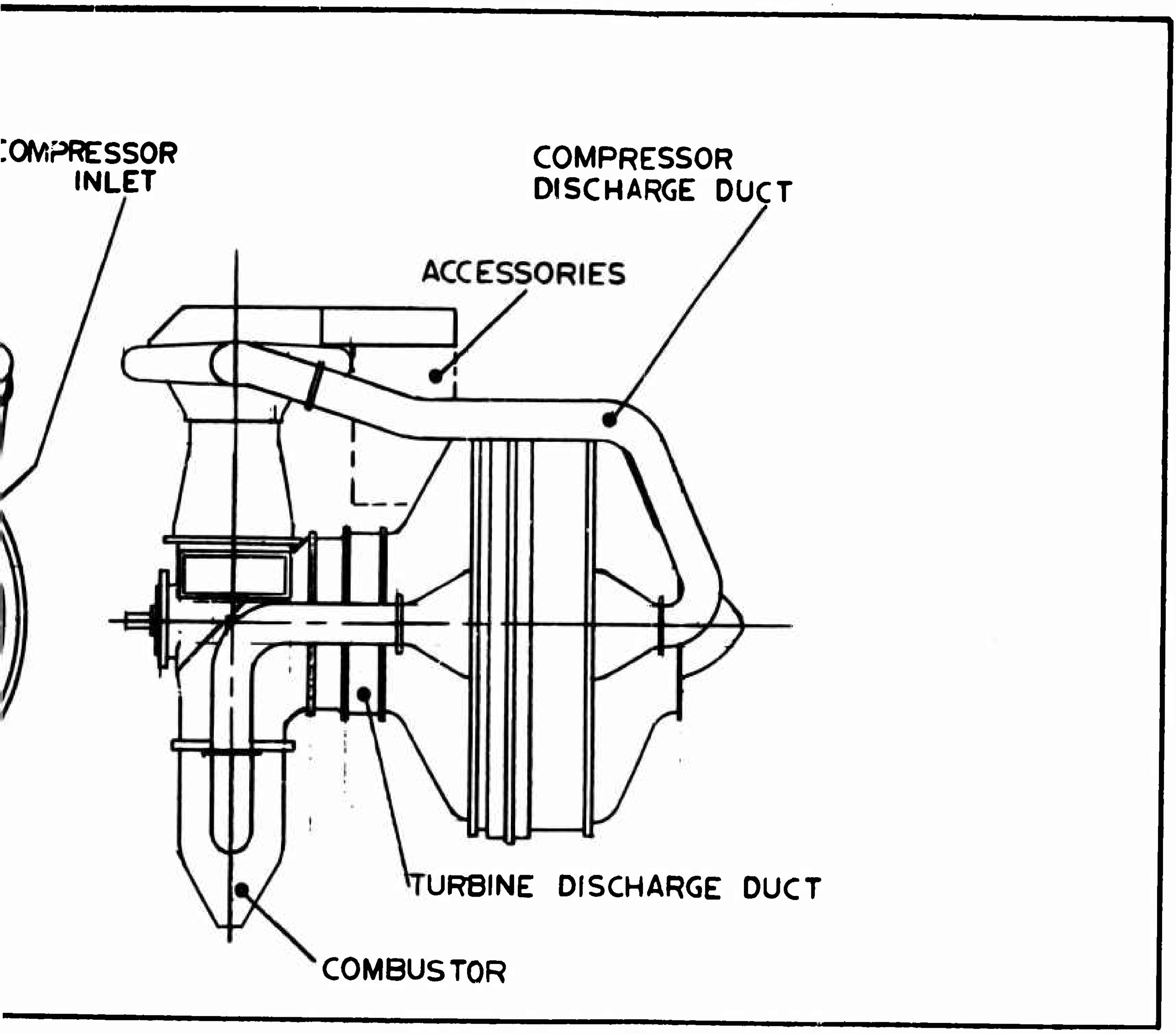


Figure 17. Typical post-turbine regenerative engine arranged with the compressor inlet between the compressor and compressor turbine, end-mounted engine accessories and combustor, and with the power turbine and rotary regenerator shaft perpendicular to the gas generator shaft.

A


COMPRESSOR INLET
COMPRESSOR DISCHARGE DUCT
ACCESSORIES
TURBINE DISCHARGE DUCT
COMBUSTOR

B

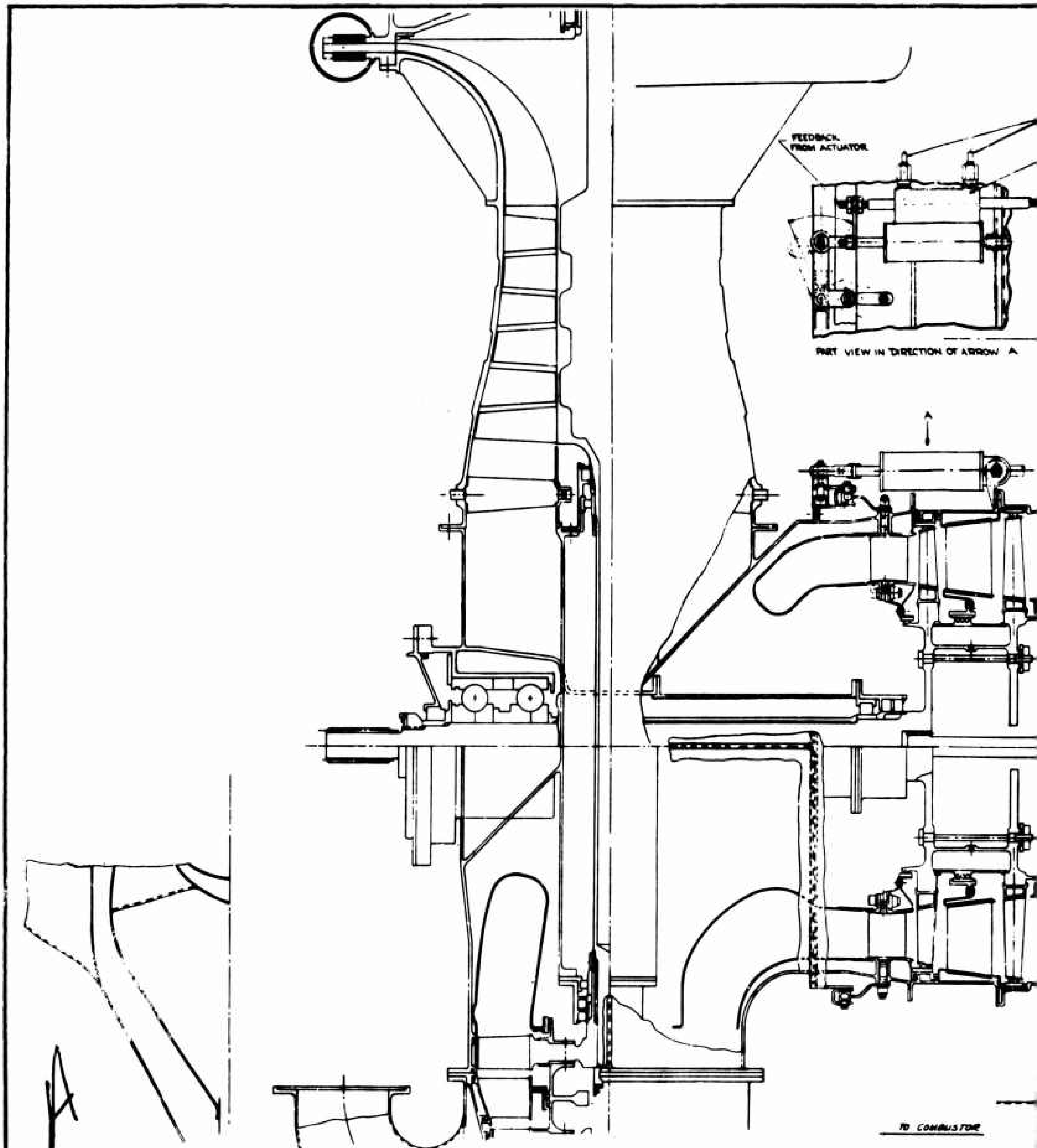
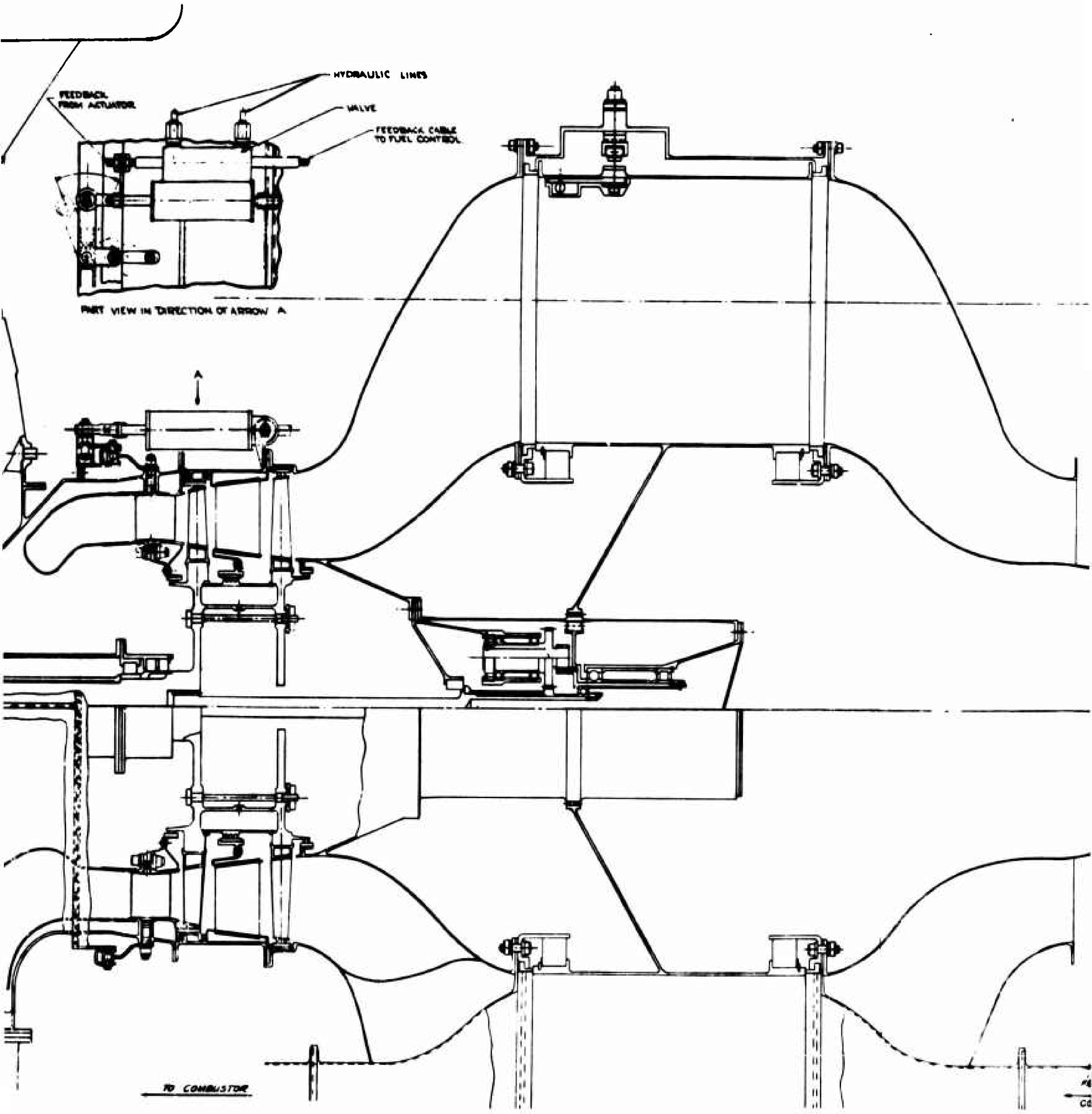


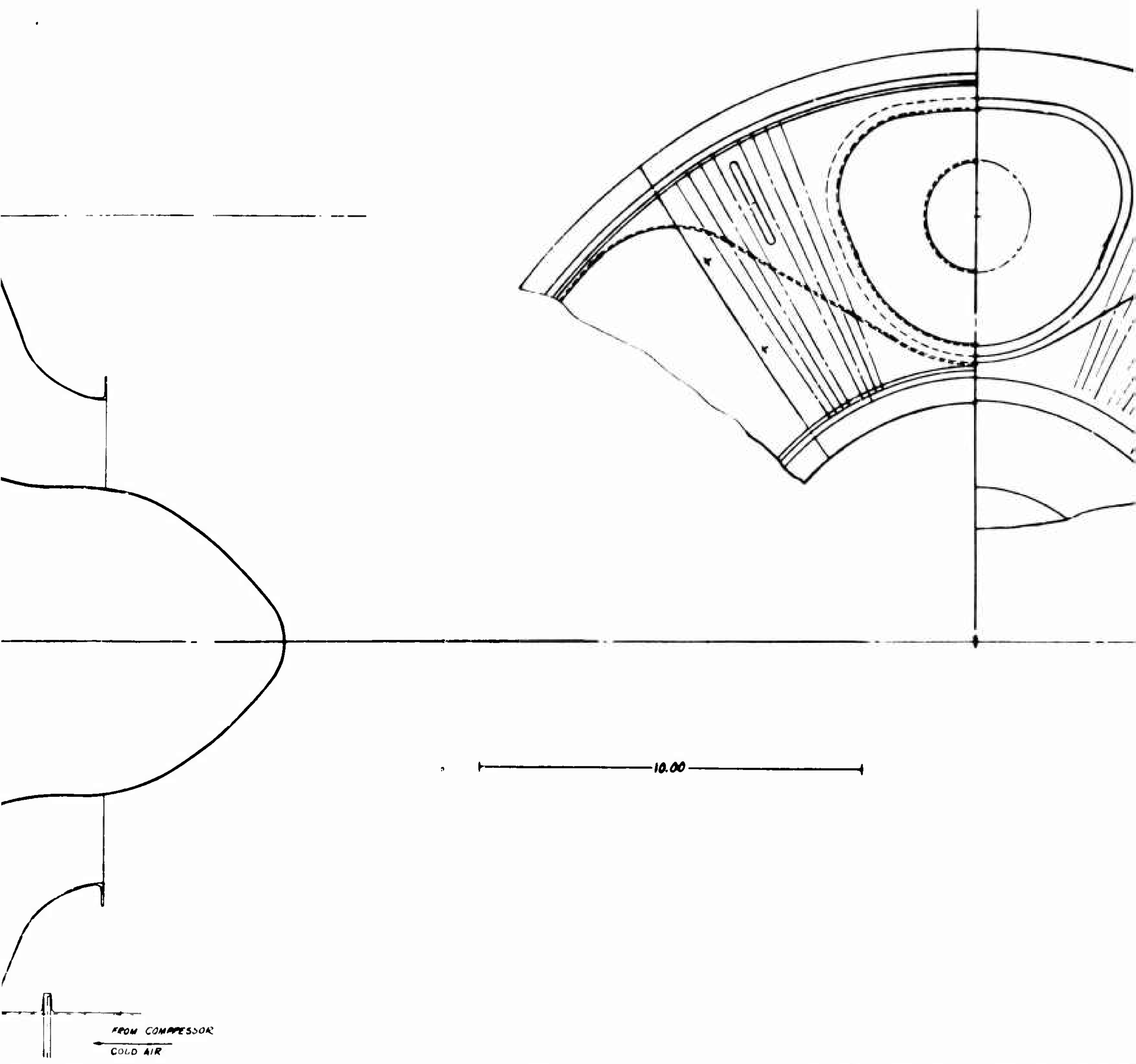
Figure 18. Typical post-turbine regenerative engine cross section.



HYDRAULIC LINES
FEEDBACK FROM ACTUATOR
VALVE
FEEDBACK CABLE TO FUEL CONTROL
PART VIEW IN DIRECTION OF ARROW A
A
TO COMBUSTOR

ction.

B.



10.00
FROM COMPRESSOR
COLD AIR

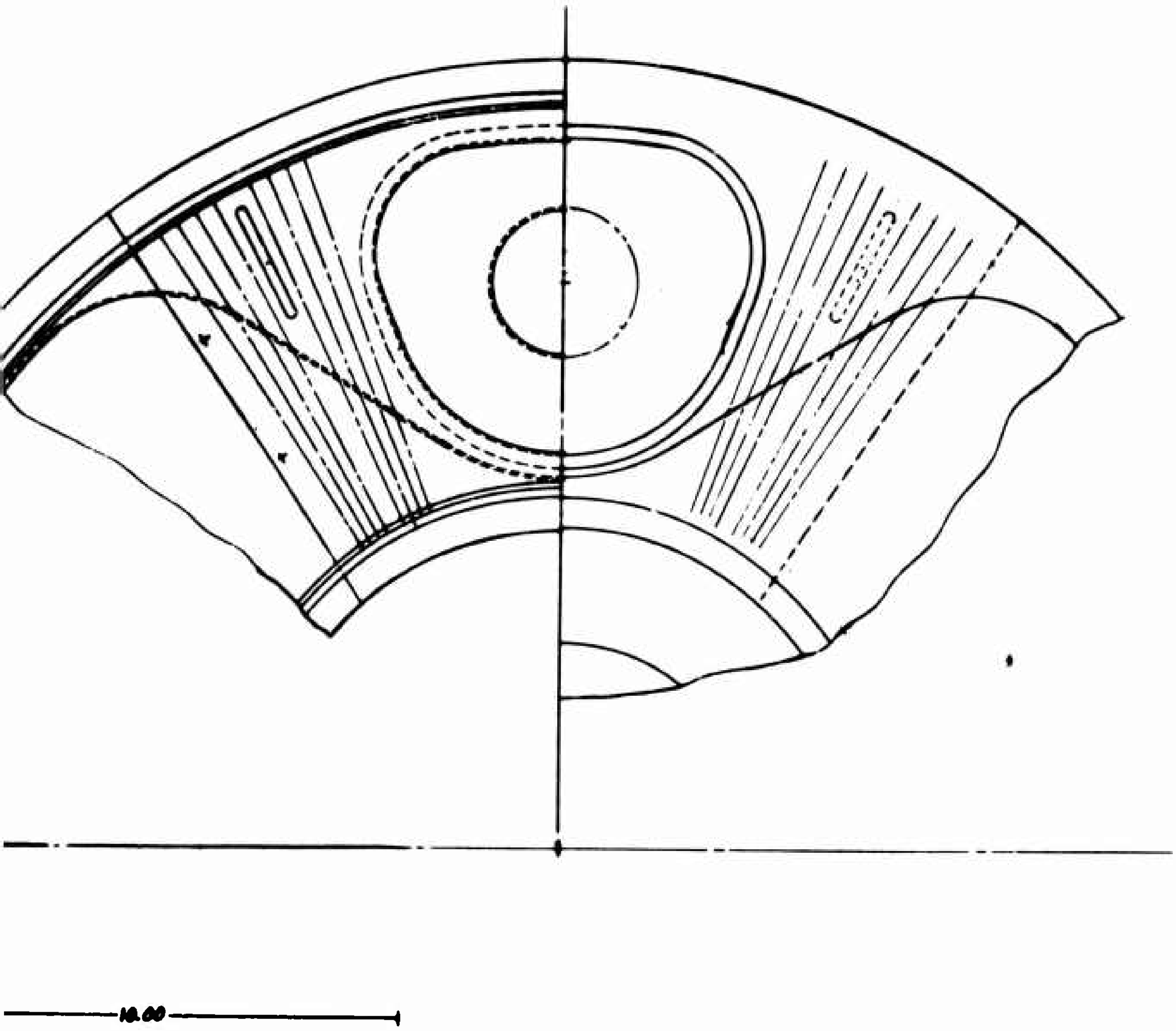


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TABLE VI

NON-REGENERATIVE ENGINE POWER OUTPUT AT EACH DESIGN POINT

Engine Operating Point	SL 59°F	3000 Ft 78°F	6000 Ft 95°F
Engine Design Point			
SL 59°F	1704	1425	1186
3000 Ft 78°F	1983	1643	1354
6000 Ft 95°F	2326	1922	1560

TABLE VII

POST-TURBINE REGENERATIVE POWER OUTPUT AT EACH DESIGN POINT

Engine Operating Point	SL 59°F	3000 Ft 78°F	6000 Ft 95°F
Engine Design Point			
SL 59°F	1520	1292	1047
3000 Ft 78°F	1716	1453	1210
6000 Ft 95°F	1947	1622	1365

TABLE VIII

INTER-TURBINE REGENERATIVE POWER OUTPUT AT EACH DESIGN POINT

Engine Operating Point	SL 59°F	3000 Ft 78°F	6000 Ft 95°F
Engine Design Point			
SL 59°F	1202	1012	853
3000 Ft 78°F	1382	1163	983
6000 Ft 95°F	1591	1342	1131

Based on the lapse rate calculated from this data, the augmentation ratio required to restore the power output at 6000 feet on a 95°F day to its value at sea level on a 59°F day is between 41 and 45 percent. This represented the upper limit on the power requirements which hot day augmentation had to meet.

DISCUSSION

The prime considerations in selecting an aircraft engine design are to obtain high power in a small, light package, with a minimum expenditure of fuel. Attainment of all goals simultaneously is, in general, impossible, and the final design results from compromising these goals to give an optimum combination for the intended application. For a gas turbine engine with the requirement of fixed output speed for all load conditions, the optimum combination has been an engine with a free power turbine operating at a temperature as high as available technology permits and at the cycle pressure ratio which gives minimum BSFC for the temperature attained. As the temperature levels attainable rise with advances in metallurgical and cooling techniques, the power available per pound of air increases; and for engines with low power requirements, the point is eventually reached where factors such as the ability to design and manufacture durable airfoil shapes play an important part in determining what the optimum engine will be. The 10 lb/sec engines being studied fall into this class; selection of the temperature, pressure ratio, and component arrangement was measurably influenced by this fact.

As shown in Figures 2 through 4, from a thermodynamic point of view, high turbine inlet temperature has payoff both in improved power output per pound of airflow and in BSFC. However, as the temperature rises, the compressor ratios required to most efficiently utilize this temperature capability also rise; and for the 10 lb/sec airflow size engines being studied, compressor mechanical and aerodynamic design problems soon become an important factor to be considered. In addition, overtemperature capability as a means of achieving power augmentation is a desirable quality in the engines under study. Weighting these factors in conjunction with the temperature capabilities predicted for engines which will be coming into use during the specified time period, a turbine inlet temperature of 2200°F was selected as the design value for all three engine types.

Based on the turbine inlet temperature selected, examination of these figures shows that a sea level static standard day, the pressure ratio for optimum fuel economy for the non-regenerative turboshaft engine is greater than 18:1, but as the ambient temperature increases, this value drops to between 16:1 and 18:1. Mechanical and aerodynamic design considerations for the compressor and turbine indicate that the highest practical pressure ratios are in the vicinity of 16:1 and 18:1 for the engines in the size range being studied. On this basis, the pressure ratio for the non-regenerative turboshaft engines was selected as a nominal value of 17:1.

Examination of Figures 5, 6, and 7 shows that for the post-turbine regenerative engine, the optimum combination of SHP and BSFC occurs at pressure ratios between 8:1 and 10:1. As compressor design is not a severe problem in this case, optimum thermodynamic performance was the prime consideration in selecting a nominal value of 9:1 as the compressor pressure ratio for these cycles.

Inter-turbine regenerative engine cycles are shown in Figures 9, 10, and 11 to achieve an optimum combination of power output and BSFC between pressure ratios of 11 to 15. Although aerodynamic and mechanical design problems are more severe for this type of engine than for the post-turbine regenerative engine, they are not yet a major factor in the design selection; on a thermodynamic basis, a nominal value of 13:1 was selected as the cycle pressure ratio for the inter-turbine regenerative engines.

Other considerations in determining the final engine layouts were:

The axial-centrifugal compressor arrangement used in all engines was chosen to eliminate the need for designing very small axial blades, while at the same time reducing the number of stages required to achieve the design pressure ratio.

For the non-regenerative engines, the gas generator compressor and turbine arrangement was influenced by mechanical problems associated with design of the high-speed rotor bearings. The offset power turbine helped in simplifying the gas generator rotor design while providing power takeoff both front and rear.

The straight-through arrangement of the inter-turbine regenerative engines was chosen, as it is the simplest configuration and since there were no overriding mechanical design problems which precluded its use. It also lends itself well to the desirable design feature of bypassing the inter-regenerator completely when high power levels are required. The engine is shown with rear drive only, but inclusion of front drive capability is possible with only minor modifications.

The arrangement of the post-turbine regenerator engine was arrived at as the design which:

Made efficient use of the volume occupied by the engine.
Simplified the regenerator ducting arrangement.
Provided for power takeoff at either end of the power turbine shaft.

The selection of the rotor regenerator design for these engines was aimed at achieving the high regenerator effectiveness in a minimum sized package. Use was made of regenerator technology already studied and tested, particularly on the rotating seals.

Inclusion of Inter-Regenerative Cycle

The inter-regenerative cycle was included as a third basic cycle to be considered for this study because of the following potential benefits:

1. While the regenerator is bypassed, large power changes of the order of 40 percent occur.

2. The inclusion of the regenerator at the point of higher gas density results in a smaller, lighter regenerator design.

3. The optimum pressure ratio of the cycle is high enough to allow consideration of common components for engines with and without regenerators.

4. The higher temperature required for the cruise power might lead to better off-design performance.

The final results showed that these benefits were not sufficient to make this engine an optimum design.

AUGMENTATION SYSTEM SELECTION

GENERATION OF CANDIDATE AUGMENTATION METHODS

To define a suitable group of candidate augmentation systems, the initial approach taken was to accept any idea proposed which fell within the area of primary interest of providing augmented engine output by effecting some temporary change in the basic engine operating mode. This approach was taken with the hope of uncovering as many promising ideas as possible, but with the intention of eliminating the marginal methods before proceeding with a detailed system study.

The list of candidates was generated by conducting searches of the technical literature on the subject and by holding a series of idea-generating or "brainstorming" sessions among groups of qualified technical personnel. The methods generated were compiled and found to fall into the following general areas:

Methods which increase power output by increasing compressor mass flow and/or reducing compressor work.

Methods which increase power by increasing the energy level and/or mass flow at the gas generator turbine inlet.

Methods which increase power by increasing the energy level and/or the mass flow at the power turbine entrance.

Methods which increase power output by decreasing losses in the engine.

In addition, several possible types of auxiliary engines were proposed, and recognition was given to the fact that combinations of the various individual methods should be examined. The complete list of proposed methods is shown in Table IX.

Reduction of the number of ideas to a workable level was accomplished by evaluating the relative potential of each method against the following criteria, and rejecting the marginal methods:

How does the method compare with similar ones which fall in the same general category?

Is the augmentation produced a significant percentage of that required to reach the program goal?

Are any technological breakthroughs necessary in order to mechanize the idea?

Are any consumable materials required to satisfy the augmentation duration excessive?

Methods remaining for detailed analysis after this initial screening process are shown in Table X.

A

TABLE IX

CANDIDATE METHODS OF PROVIDING HOT DAY AND/OR EMERGENCY POWER AUGMENTATION

<u>Methods Which Increase Engine Mass Flow and/or Reduce Compressor Work</u>

Pre-compressor injection of liquids.

- Water-alcohol
- Water
- Ammonia
- Liquid nitrogen
- Liquid CO_2
- JP_4
- Freon (11, 12, 22)
- Trichlorethylene
- Other fluids available in the field

Supercharging of the compressor, using a zero stage driven by:

- An auxiliary air turbine using stored air with the cold exhaust air mixed into the compressor inlet for refrigeration purposes.
- A tip turbine using air bled from the compressor and heated in a separate burner.
- A tip turbine using a stored monopropellant.
- Through-gears and a clutch attached to the gas generator.
- Through-gears and a clutch attached to the power turbine.

Intercooling the compressor, using stored coolants.

High-flowing the compressor by utilizing variable geometry beyond its normal limits.

A tip turbine using a stored monopropellant.

Through-gears and a clutch attached to the gas generator.

Through-gears and a clutch attached to the power turbine.

Intercooling the compressor, using stored coolants.

High-flowing the compressor by utilizing variable geometry beyond its normal limits.

High-flowing the compressor by bleeding with reinjection of the bleed flow back into a variable-geometry power turbine.

Pre-cool the compressor inlet flow, using "heat pipes" and a stored coolant.

Overspeed and overtemperature.

Methods Which Increase the Energy Level and/or Mass Flow at the Gas Generator Turbine Inlet

Increase turbine mass flow by injection of liquids into the combustor along with additional fuel to hold constant T_4

Overtemperature at constant-speed clutching in the free power turbine through appropriate gear ratio to prevent gas generator overspeed with emergency T_4 levels.

Methods Which Increase the Energy Level and/or the Mass Flow at the Power Turbine Inlet

Interburning

Injecting hot gases from

Solid or liquid monopropellant system

Separate gas generator

Methods Which Decrease Losses in the Engine

Bypassing the regenerator

Bypassing the inter-regenerator

Auxiliary Systems

Third simple but inefficient engine

Chemically fueled power turbine

Overspeed and overtemperature.

Methods Which Increase the Energy Level and/or Mass Flow at the Gas Generator Turbine Inlet

Increase turbine mass flow by injection of liquids into the combustor along with additional fuel to hold constant T_4

Overtemperature at constant-speed clutching in the free power turbine through appropriate gear ratio to prevent gas generator overspeed with emergency T_4 levels.

Methods Which Increase the Energy Level and/or the Mass Flow at the Power Turbine Inlet

Interburning

Injecting hot gases from

- Solid or liquid monopropellant system
- Separate gas generator

Methods Which Decrease Losses in the Engine

- Bypassing the regenerator
- Bypassing the inter-regenerator

Auxiliary Systems

- Third simple but inefficient engine
- Chemically fueled power turbine
- Steam powered turbine using the main engine combustor as a boiler
- A high-flow, low-pressure-ratio engine with the compressor driven by the main engine power turbine with all output supplied to the rotor.

C

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TABLE X ALTITUDE HOT DAY AND EMERGENCY POWER AUGMENTATION METHODS FOR DETAIL STUDIES
Pre-Compressor Water Injection
Pre-Compressor Ammonia Injection
Pre-Compressor Water-Alcohol Injection
Compressor Supercharging, Using a Tip-Turbine-Driven Zero Stage
Compressor Intercooling
Overspeed and Overtemperature
Combustor Liquid Injection
Overtemperature at Constant Speed
Using a Variable-Geometry Turbine
Interburning
Injection of Hot Gases from a Monopropellant
Combustion System Between the Turbines
Bypassing the Regenerator
Bypassing the Inter-regenerator
Combination of One or More of the Simple Systems
An Auxiliary Power Turbine Using a Monopropellant Energy Source

DISCUSSION OF THE BASIS FOR REJECTION OF SYSTEMS

The effect of pre-compressor liquid injection on the operation of an engine is based on the fact that evaporation of the liquid reduces the temperature of the mixture passing through the compressor, allowing the compressor to pass more flow at a reduced rate of work per unit weight of flow. A measure of the value which can be credited to this type of system is the amount of change in performance per - cent liquid injected. This is a function of the latent heat of vaporization of the liquid and the position in the air flow path where the vaporization occurs.

Extremes in the position where the evaporation takes place are from all of it occurring ahead of the compressor to all of it occurring within the compressor.

Of all the liquids considered, water and water-alcohol mixture have the highest latent heats, and ammonia is third. Since water and water-alcohol represent the exterme of all vaporization within the compressor and since ammonia represents the extreme of all vaporization in front of the compressor, these liquids were selected for detailed study; all others were rejected as similar systems with inferior potential. Pre-cooling of the compressor by other methods was also rejected as an inferior variation on this method.

Of the various supercharging methods proposed, the monopropellant driven tip turbine was accepted, based on the fact that it did not subtract power from the cycle to drive it and, as such, would be capable of providing 60 percent more augmentation than the methods which extracted power from the cycle through air bleed or clutch drive arrangements. Monopropellant was selected as the working fluid in preference to the cold air storage system based on a lower consumable stores requirement.

High-flowing of the compressor by bleeding or by utilizing variable compressor geometry beyond its normal limits was rejected, based on the fact that these methods are only useful in improving performance at low corrected speeds, where mismatching occurs among the compressor stages. At the high corrected speeds of interest in this study the stage matching is near optimum, and the means suggested to increase flow will more than likely reduce engine output by introducing mismatch conditions.

Overspeeding of the gas generator portion of the engine at constant turbine inlet temperature gives little or no improvement in power because as Figure 19 shows the increasing pressure ratio and decreasing compressor efficiency which occur with overspeed decrease the engine power output as fast as the airflow gain increases it. In fact at the non-regenerative engine pressure ratio of 17:1, where the effect of compressor efficiency on engine performance is greater, the power output decreases with overspeed at constant temperature. Therefore this method of augmentation was rejected as a condidate for further investigation.

At the high power levels required for takeoff, the power turbine is normally running choked or very close to choked. Under these conditions, increases in flow or temperature at the turbine entrance without increases in pressure cannot be accommodated by the turbine without increasing the entrance area. The amount of area increase which can be obtained in the turbines selected is limited to 12 percent. The method which most effectively uses this area increase in maximizing augmentation is to increase temperature rather than mass flow. This stems from the fact that while power output increases directly with increases in either temperature or flow, the area increase required goes up only as the square root of

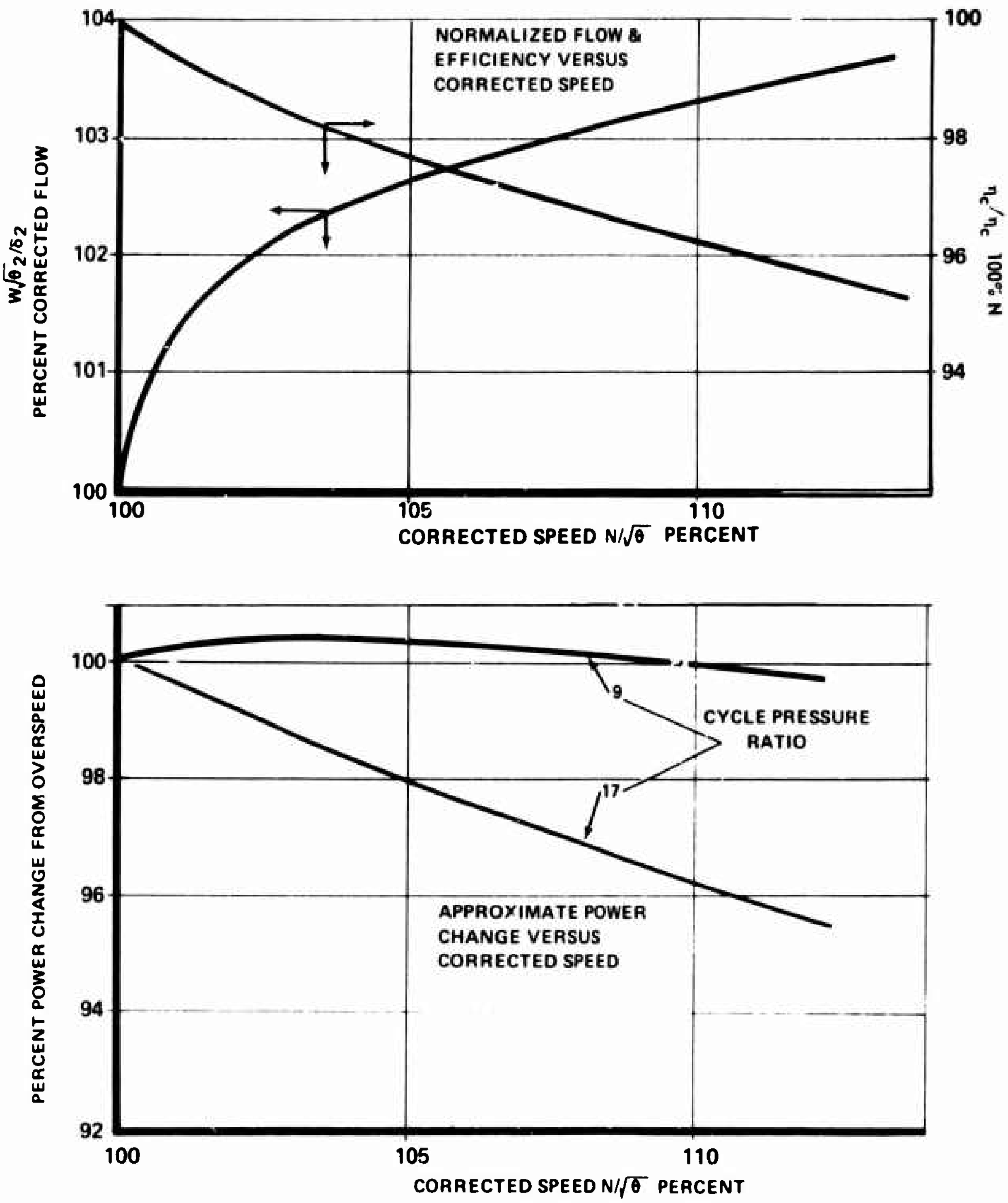

Figure 19. Trends in compressor flow and efficiency and engine power output during overspeed at constant temperature.

temperature but directly with flow, and for the 12 percent area change available, increases in flow give only a 12 percent power boost while increased in temperature give a 25 percent power boost. On this basis, interburning was evaluated as the most promising candidate in this general category.

Auxiliary power sources were not the area of primary interest in this study; therefore, the decision was made to investigate them on a low-priority basis. The problem in considering an auxiliary is primarily one of weight, since without weight considerations it is always possible to build an auxiliary of sufficient power to accomplish the job required. Of the auxiliaries suggested, those which drew all of their working fluid from storage were not practical for the hot day application because, at the required power levels, flow requirements were 2.5 pounds/second and the weight of flow for 5 minutes of 750 pounds was above the acceptable level.

The gas turbine engines considered as auxiliary power sources have the same hot day altitude lapse rate problems as the basic engine; and to achieve the power required to make up for power loss in two basic engines, the auxiliary engine must be 88 percent as large as the basic engine. This is an attractive system technically, but it raises questions of the economic feasibilites of putting three engines on a twin-engine vehicle, and study of the economic aspects of supplying augmentation were outside the contract scope.

Monopropellant auxiliaries are feasible for a 1-minute emergency power requirement. To evaluate the relative value of these systems, a design using a chemically fueled power turbine was analyzed as part of the study.

EVALUATION OF AUGMENTATION SYSTEM THERMODYNAMIC PERFORMANCE

GENERAL METHOD OF ANALYSIS

Evaluation of the augmentation system was carried out in the following manner.

An augmentation system based on one or a combination of the methods selected for study was incorporated into one of the basic engines, and engine power output was calculated using the available time-sharing computer programs. The computations were performed either at 6000-foot static 95°F ambient temperature conditions or at sea level static standard conditions, depending on whether takeoff under hot day altitude or emergency power conditions was being studied. For each system, the augmenting parameter was varied over a range of values which gave outputs from unaugmented to the maximum possible within the limits imposed by the engine and/or the augmentation system. The calculated results were presented as plots of the ratio of augmented to unaugmented power outputs versus the augmenting parameter. Figures 24 through 53 are used as working curves in establishing the augmentation system design requirements.

General assumptions used in generating these results were:

1. Except as otherwise noted, the engine is assumed to be running at its rated turbine inlet temperature of 2200°F. Gas generator physical overspeed is therefore implicit in many of the augmentation methods presented.

2. The compressor operating line characteristics are shown in Figures 20 through 23.

3. In all cases where augmentation systems are applied to the regenerative or inter-regenerative engines, the engine is operating with the regenerator bypassed.

4. The operating limit of the compressor is 110 percent corrected speed with no limit applied to physical speed.

5. The performance levels of the basic engine components remain unchanged.

Assumptions applying to specific augmentation methods were:

1. All evaporation of water or water-alcohol mixtures injected in front of the compressor takes place during a wet compression process within the compressor. This process was simulated on the computer, using

the method of P.G. Hill, which calculates multipliers for use in modifying the compressor flow and efficiency used in determining engine performance. These multipliers are dependant on the liquid to air ratio and latent heat of the liquid injected, and have been verified by the results of water injection tests run on T64 engines.

2. Ammonia injected in front of the compressor evaporated before entering the compressor and mixed uniformly with the air, resulting in reduced inlet temperature.

3. The design point characteristics of the zero-stage supercharger were as shown in Tables XI and XII.

4. Pressure loss on the air side of the intercooler was 3.25 percent.

5. Cooling medium for the intercooler was water.

6. Intercooling was done at the optimum point, which is at the square root of the overall pressure ratio.

7. Interburner pressure loss was 5 percent, and was independent of interburner temperature rise.

RESULTS OF HOT DAY AUGMENTATION CALCULATION

Compressor Inlet Water or Water-Alcohol Injection

Augmentation ratios obtainable from injection of water or water-alcohol mixtures into the compressor inlet vary directly with water/air ratio and the type of engine to which it is applied (Figure 24). At a water/air ratio of .025, the augmentation ratios obtained were 47 percent for the non-regenerative engine and 43 percent for the post-turbine regenerative engine. Performance was not calculated for the inter-turbine regenerative engine, but the prediction method used would give results intermediate to those shown.

A mixture of 35 percent alcohol and 65 percent water would give the same results except that the liquid-air ratio for equal values of augmentation ratio would be 1.25 times the values for water due to the lower latent heat of vaporization. However, the heating value of the alcohol would decrease the amount of additional main fuel required, to the degree to which the alcohol burned.

Pre-Compressor Ammonia Injection

In calculating engine performance with pre-compressor ammonia injection two different control models were used.

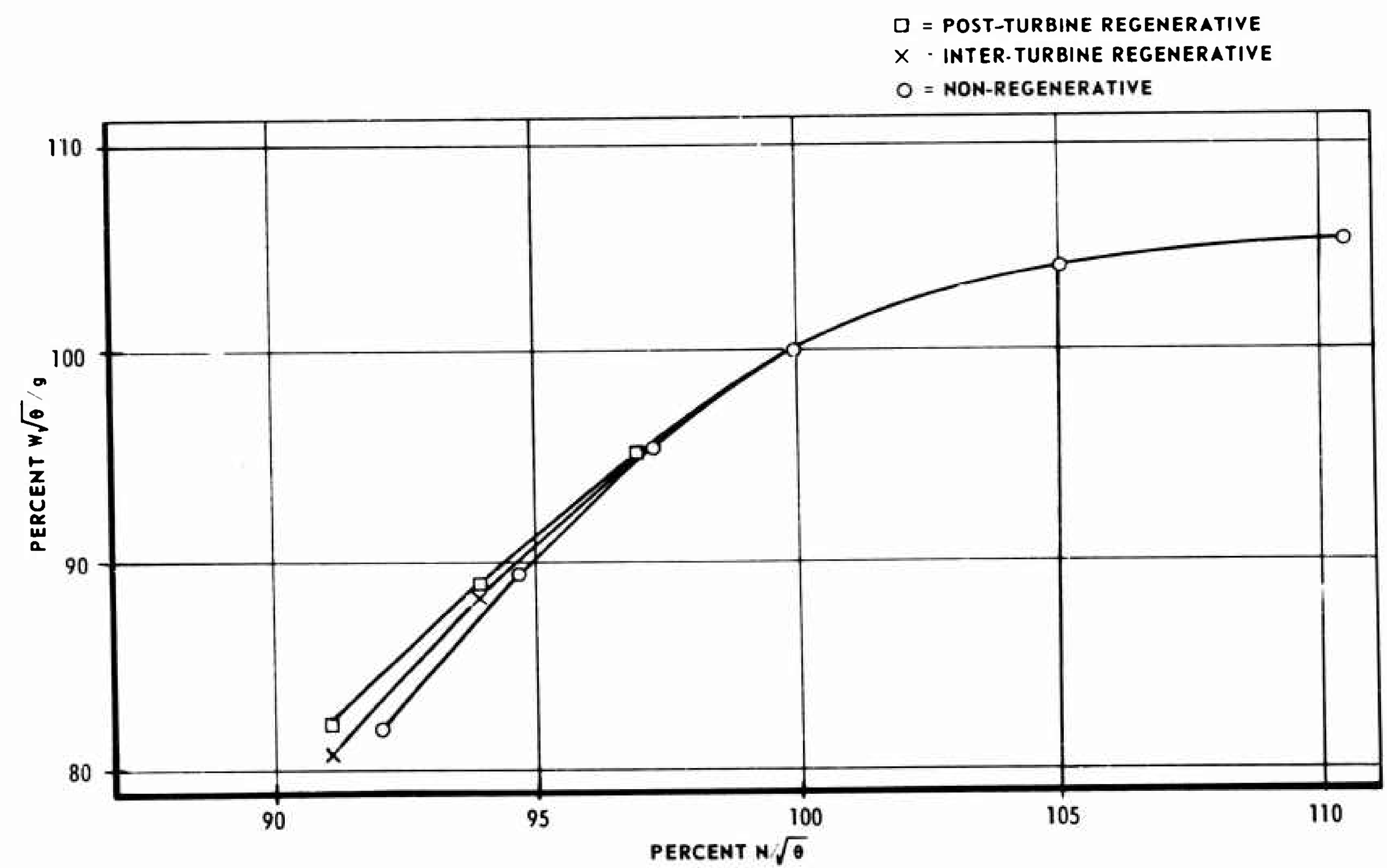

Figure 20. Assumed compressor operating line characteristics, percent corrected flow versus percent corrected speed.

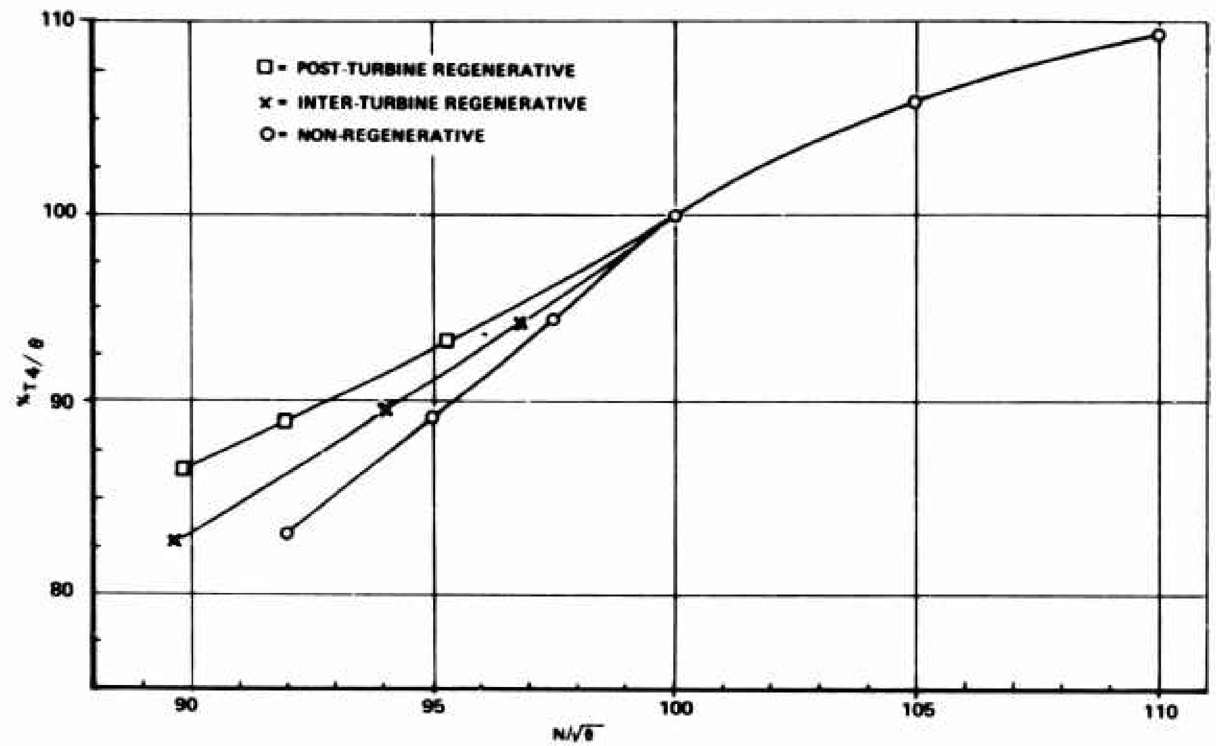

Figure 21. Assumed compressor operating line characteristics, percent corrected turbine inlet temperature versus percent corrected speed.

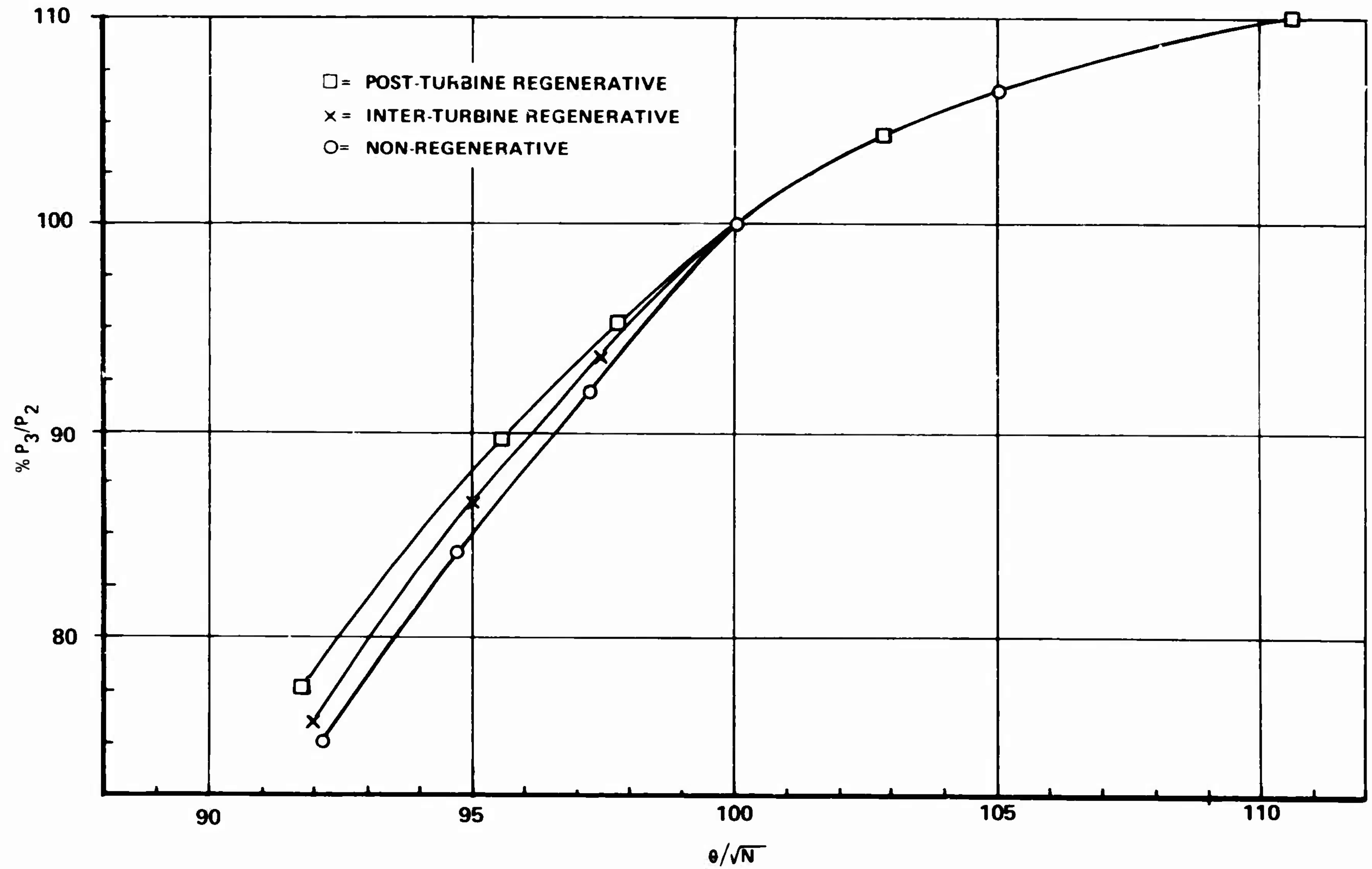

Figure 22. Assumed compressor operating line characteristics, percent design pressure ratio versus percent corrected speed.

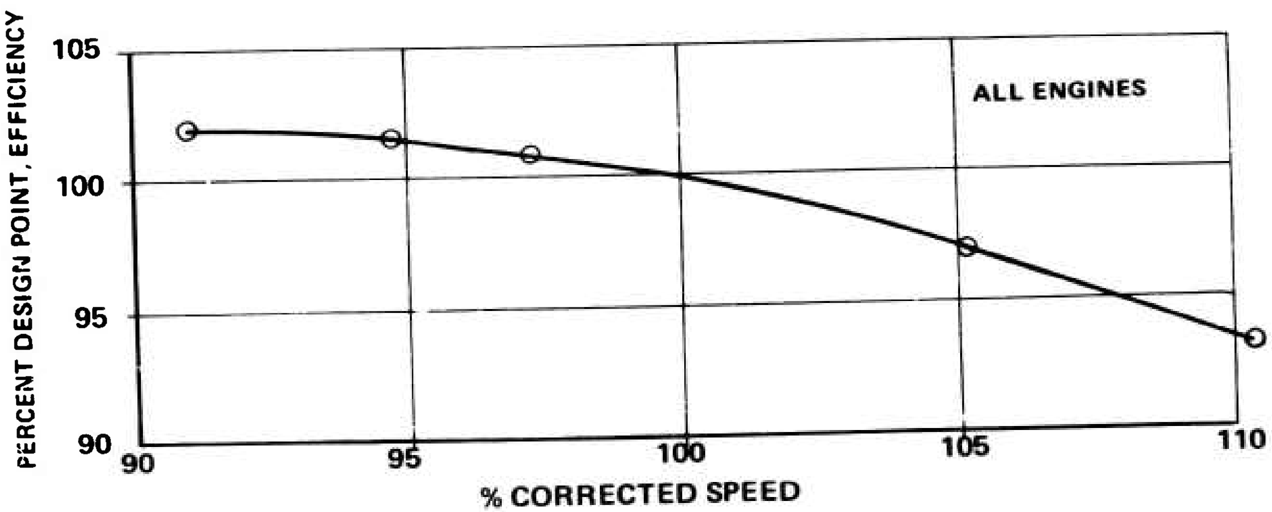

Figure 23. Assumed compressor operating line characteristics, percent design point efficiency versus percent corrected speed.

TABLE XI

ZERO STAGE TIP TURBINE DESIGN REQUIREMENTS

Fuel	JP4/Air	Steam	NH_3	H_2O_2	N_2H_4
Wt Flow - lb/sec	1.09	1.14	1.13	1.24	1.11
Arc of Admission	52°	53°	57°	115°	148°
Inlet Total Temp - °R	2200	1259	1259	2250	2160
Inlet Total Pressure - psia	47.5	48.1	44.55	28.5	23.3
Total - Static Efficiency - %	66	67	66	72	71
Exit Swirl - °	2°	0	0	-3°	3°
Exit Mach No.	.678	.67	.644	.433	.384
Δh - btu/lb	105	100	100	90	100

TABLE XII

ZERO STAGE SUPERCHARGER DESIGN REQUIREMENTS

Fan Tip Radius (Constant)	4.8 in.
Fan Hub Radius (Rotor Inlet)	2.88 in.
Fan Hub Radius (Rotor Outlet)	3.10 in.
Fan Hub Radius (Stator Outlet)	3.20 in.
Rotor Stagger (Tip Section)	54.65°
Rotor Stagger (Hub Section)	32.50°
Rotor Camber (Tip Section)	2.90°
Rotor Camber (Hub Section)	20.00°
Rotor Solidity (Tip Section)	1.0
Rotor Solidity (Hub Section)	1.6
Number of Blades	24
Rotational Speed	25000
Inlet Pressure	12.0 $lb/in.^2$
Inlet Temperature	553.7°R
Pressure Ratio (Overall)	1.26
Adiabatic Efficiency	0.85

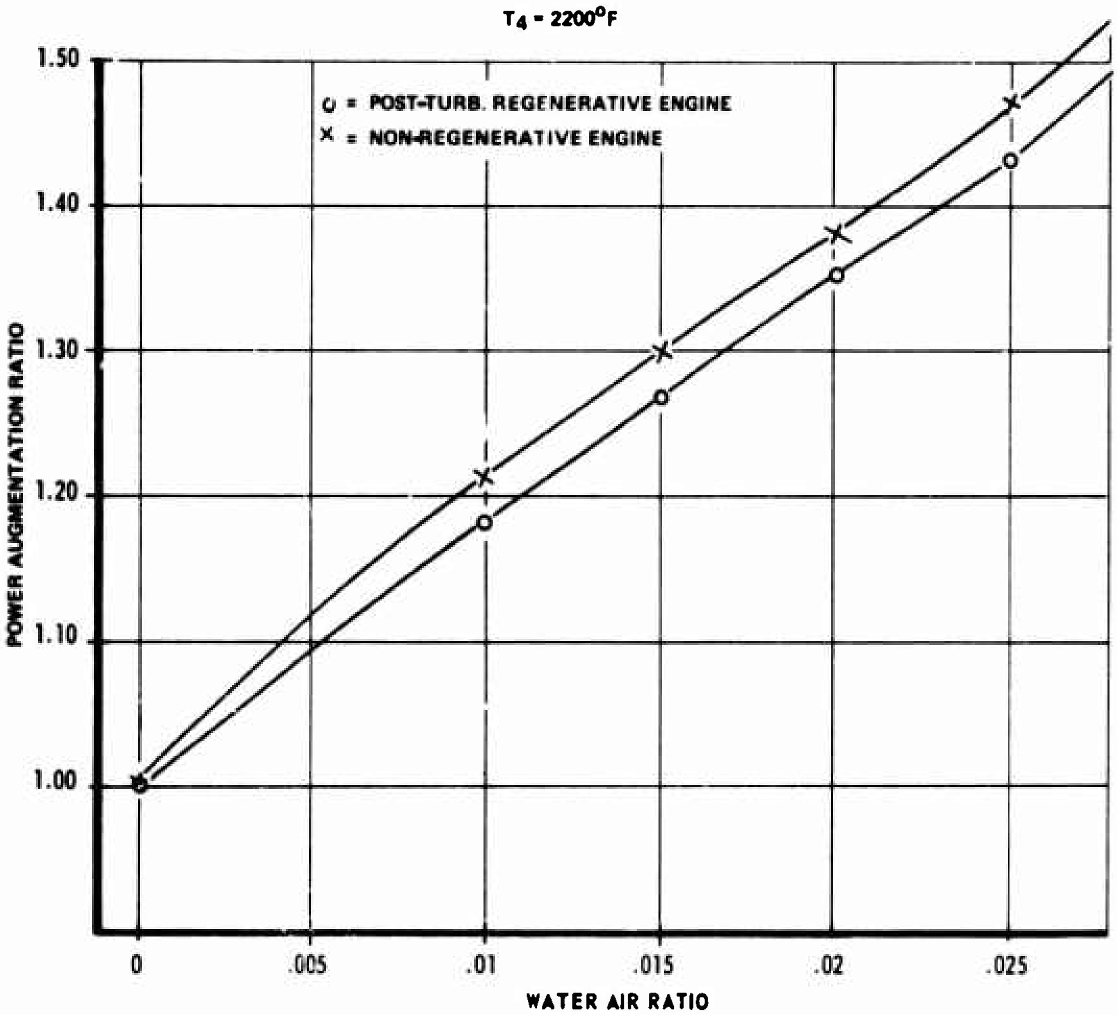

Figure 24. The effect of compressor inlet water injection on power augmentation ratio, 6000 feet static, T ambient = 95°F.

The first was a constant 100 percent physical speed up to a corrected speed limit of 105 percent and then constant corrected speed. As shown in Figure 25, the augmentation reached maximum values of 32 percent and 30 percent for the non-regenerative and post-turbine regenerative engines, respectively, at an ammonia/air ratio of 4 percent and then decreased as the ammonia/air ratio was increased. The decrease was caused by the reduction in turbine inlet temperature required to hold the speed at the corrected limit imposed. The compressor inlet temperature at maximum augmentation was calculated to be 17°F. The augmentation ratio greater than 1.0 for the post-turbine regenerative engine at zero ammonia/air ratio is caused by the overtemperature which exists in this engine at 100 percent physical speed.

The second control used constant turbine inlet temperature, letting the engine operate to a corrected speed limit of 110 percent. As shown in Figure 27, this control mode yields about 4 percent higher power output than the constant-speed control mode, with a larger gain for the post-turbine regenerative engine than for the non-regenerative engine.

The use of pre-compressor ammonia injection on an engine equipped with a variable area power turbine kept the engine operation in a more favorable position on the compressor operating characteristic and permitted use of high ammonia/air ratio with the potential for achieving augmentation ratios of 52 percent at an ammonia/air ratio of 6 percent (Figure 27).

Zero Stage Supercharging Separately and in Combination with Ammonia Injection

Augmentation ratios obtained from the tip-turbine-driven supercharger were dependent on engine type, as shown in Table XIII.

TABLE XIII

AUGMENTATION RATIOS USING A ZERO STAGE SUPERCHARGER

ENGINE TYPE	AUGMENTATION RATIO
Post-Turbine Regenerative	11.5%
Inter-Turbine Regenerative	15.5%
Non-Regenerative	17.7%

To improve this low level of augmentation, pre-compressor ammonia injection was combined with the supercharging. The resulting augmentation ratios, shown

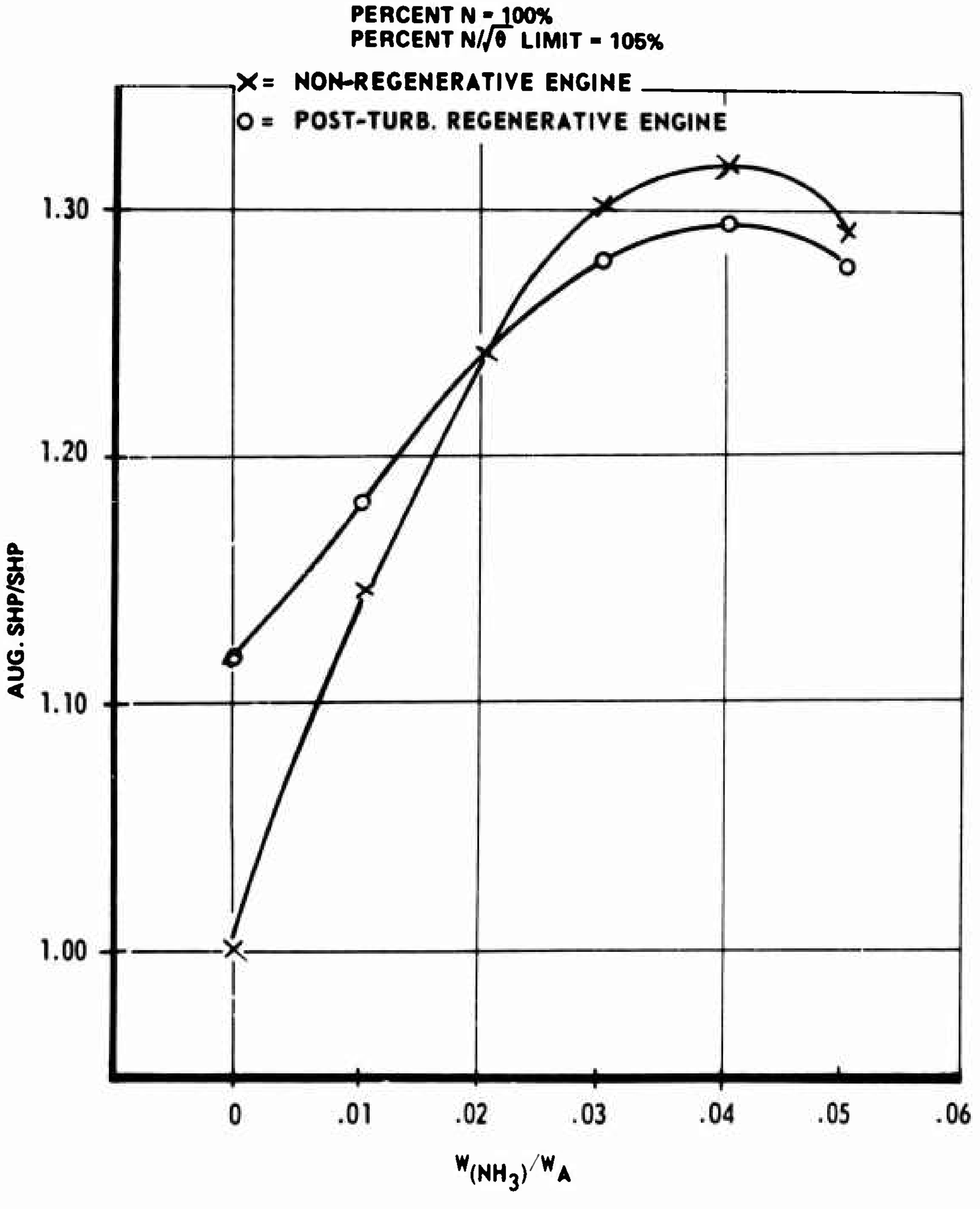

Figure 25. The effect of pre-compressor ammonia injection on power augmentation ratio, 6000 feet static, T ambient = 95°F.

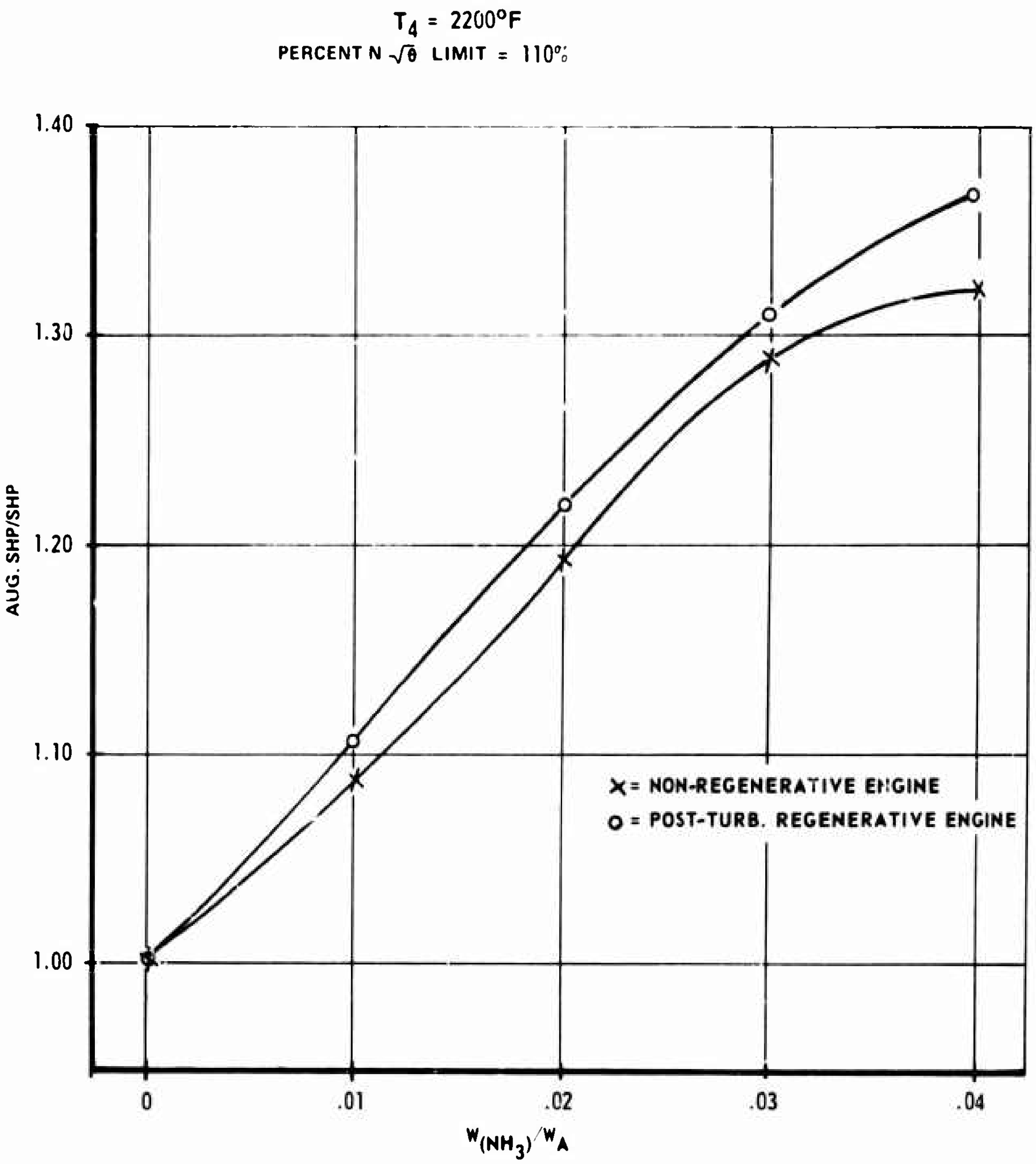

Figure 26. The effect of pre-compressor ammonia injection on power augmentation ratio, 6000 feet static, T ambient = 95°F.

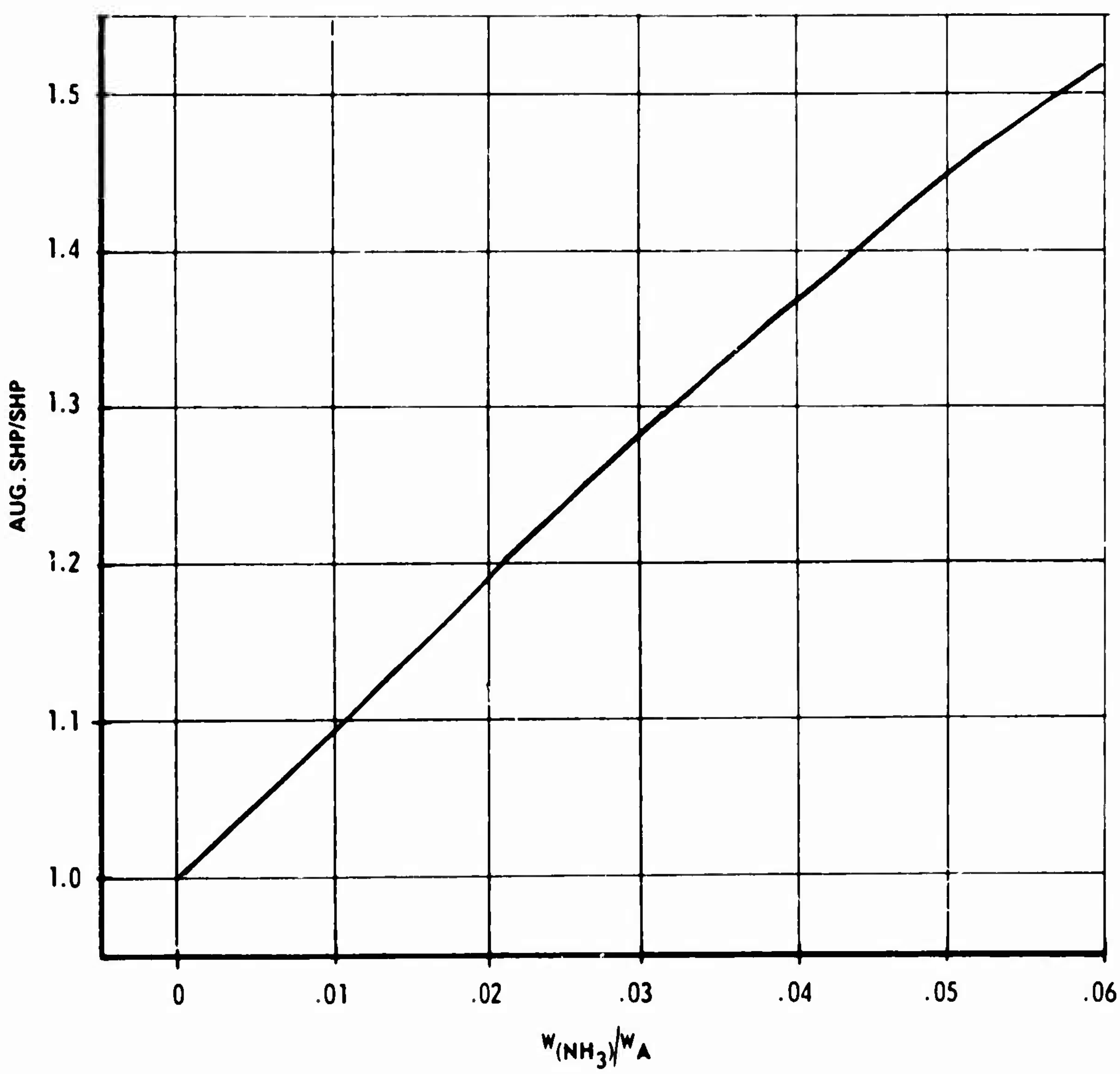

Figure 27. The effect of pre-compressor ammonia injection on the augmentation ratio of a non-regenerative engine equipped with a variable area power turbine.

in Figures 28 through 30, reached the required level in the vicinity of a 2 percent ammonia/air ratio.

Compressor Intercooling

Intercooling as an augmentation method was possible in any of the basic engines, but calculations were made only for the non-regenerative engine, where intercooling was of more interest due to the higher pressure ratio and two-spool compressor design. Three different engine operating modes were studied, two of which used a variable-area power turbine. Control modes used with the variable turbine were T_4 and T_5 control. The third used T_4 control and a fixed power turbine. The first two methods allow use of the intercooler to its design effectivness of 79 percent without introducing excessive changes in gas generator rpm. The third method does not permit full use of the intercooler potential, as the gas generator overspeeds to its limiting value at an intercooler temperature drop of 125°F.

Figure 31 shows that the maximum augmentation available with variable power turbine and constant turbine inlet temperature is 41 percent at an intercooler temperature drop of 250°R.

Figure 32 shows that the maximum for constant turbine discharge temperature is 34 percent.

Figure 33 shows that for the engine with fixed power turbine, engine overspeed considerations limit the maximum augmentation to 21 percent.

Combustor Liquid Injection

The augmentation ratio obtained from injection of liquid into the combustor, over the range from 0 to .11 liquid/air ratio, was independent of engine type; at the .11 value of liquid/air ratio, the augmentation ratio was 1.35 (Figure 34). Compressor stall margin at this value was down from 20 percent to 7 percent.

Gas Generator Turbine Overtemperature

Engine augmentation available from overtemperaturing the gas generator turbine was determined for turbine inlet temperatures up to 2930°R. The non-regenerative engine was investigated first for two engine operating modes: (1) overspeed and overtemperature and (2) overtemperature at constant speed using a variable-area gas generator turbine. As shown on Figure 35, the augmentation ratio is linear with temperature and independent of engine operating mode. The maximum augmentation calculated was 34 percent at 2930°R. The absolute power output for the variable area turbine engine is slightely lower due to the lower design point efficiency for the variable area turbine.

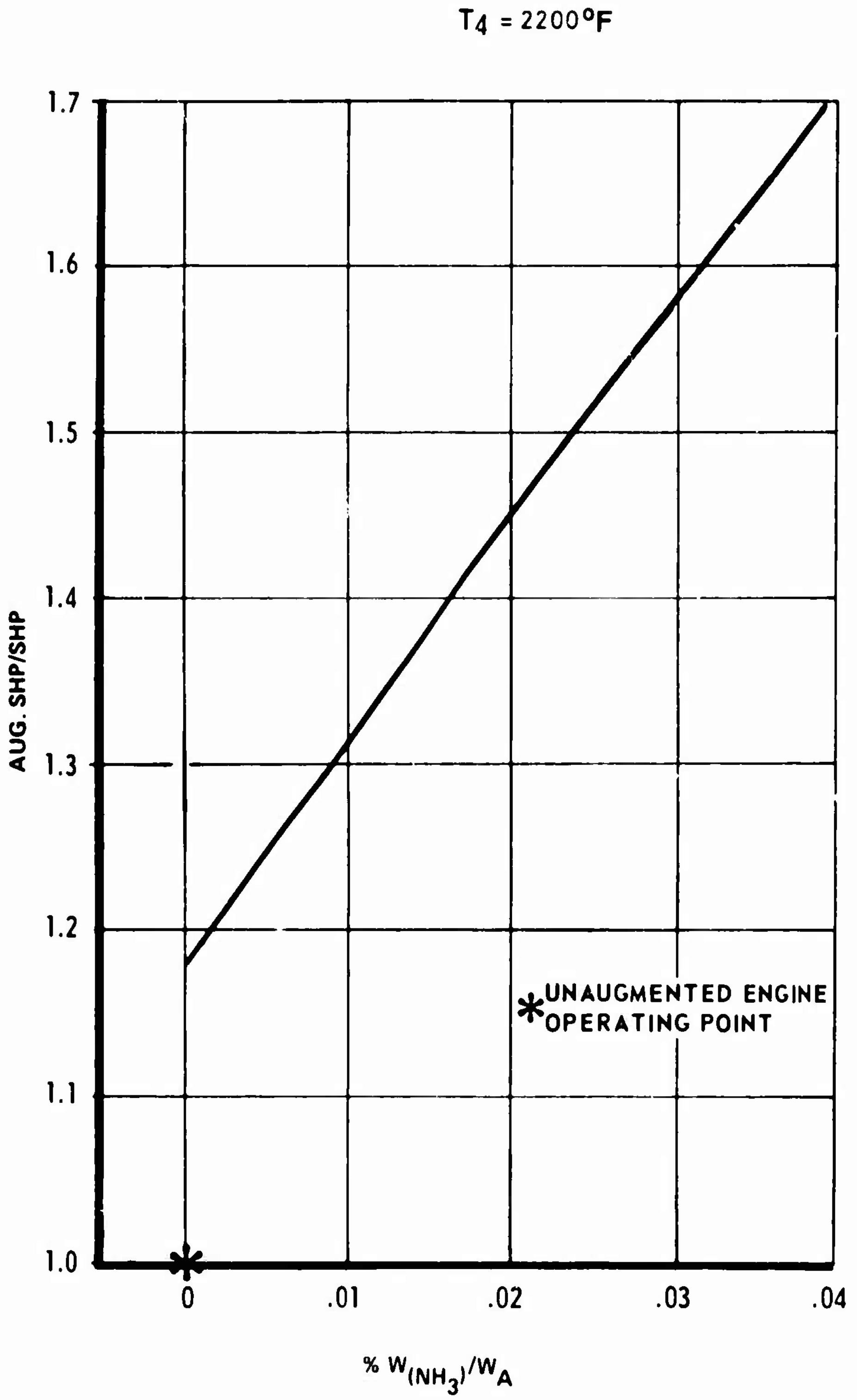

Figure 28. The effect of combined zero stage supercharging and presupercharger ammonia injection on the power augmentation ratio of a non-regenerative engine, 6000 feet static, T ambient = 95°F.

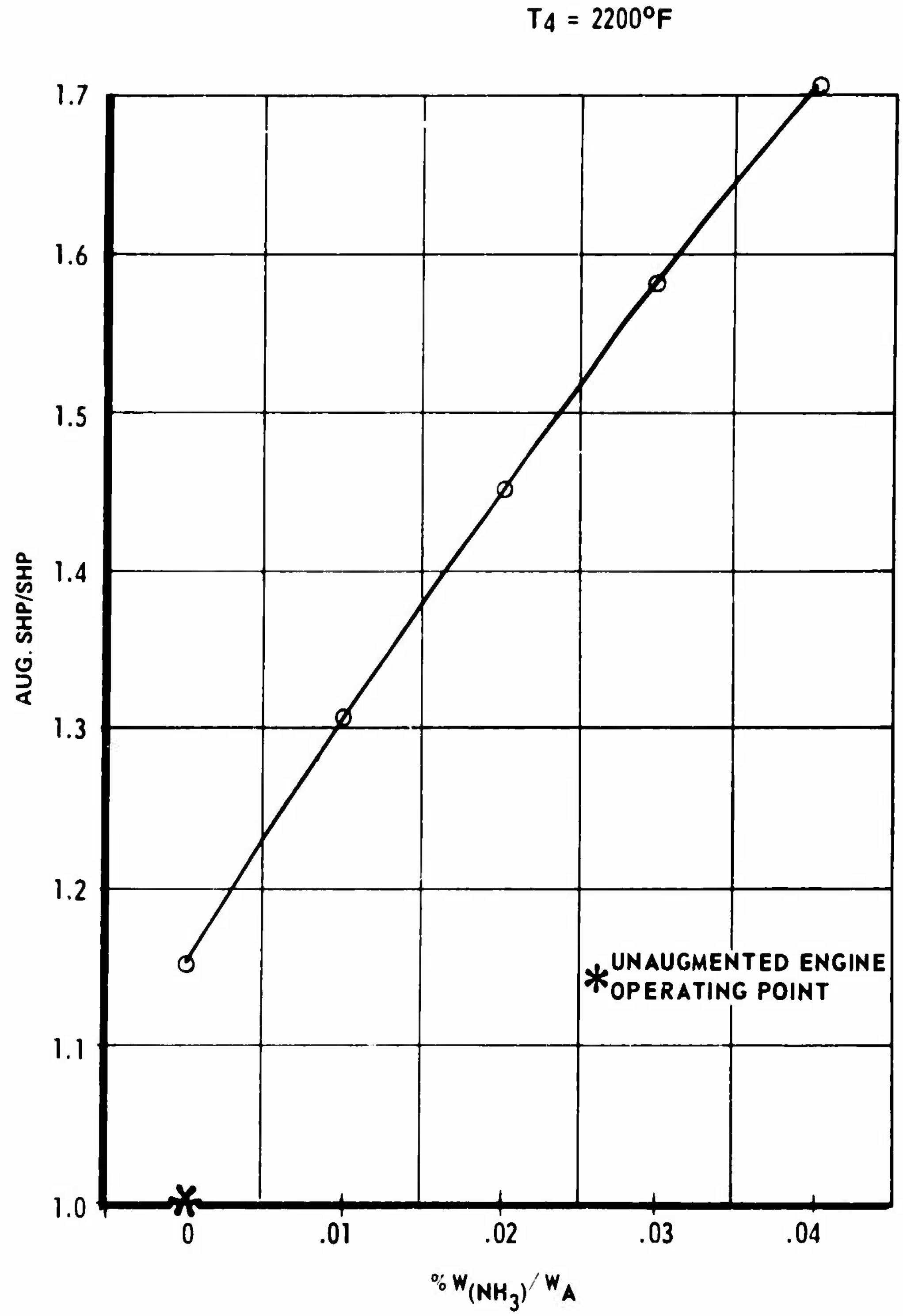

Figure 29. The effect of combined zero stage supercharging and presupercharger ammonia injection on the power augmentation ratio of an inter-turbine regenerative engine, 6000 feet static, T ambient = 95°F.

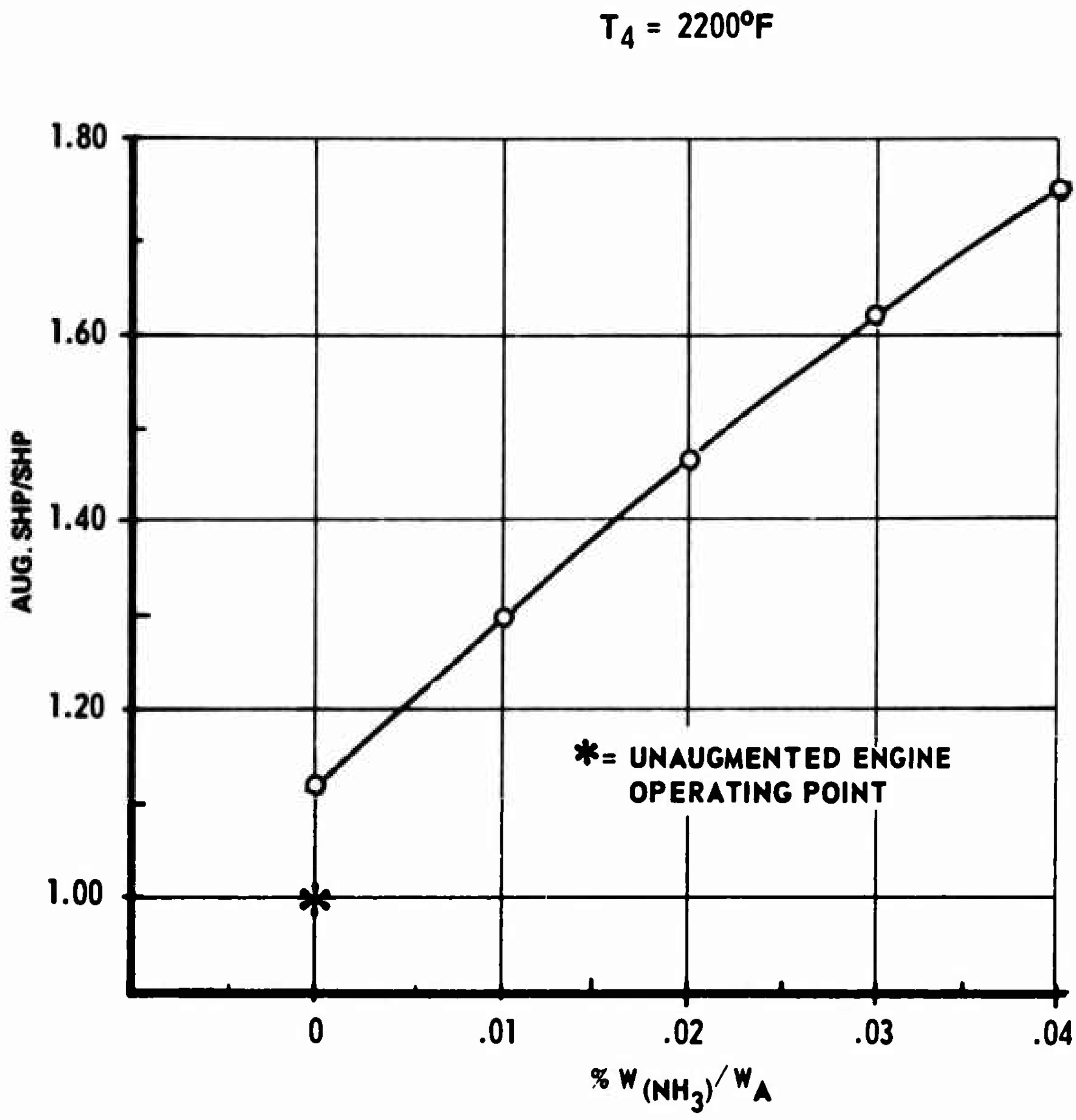

Figure 30. The effect of combined zero stage supercharging and presupercharger ammonia injection on the power augmentation ratio of a post-turbine regenerative engine, 6000 feet static, T ambient = 95°F.

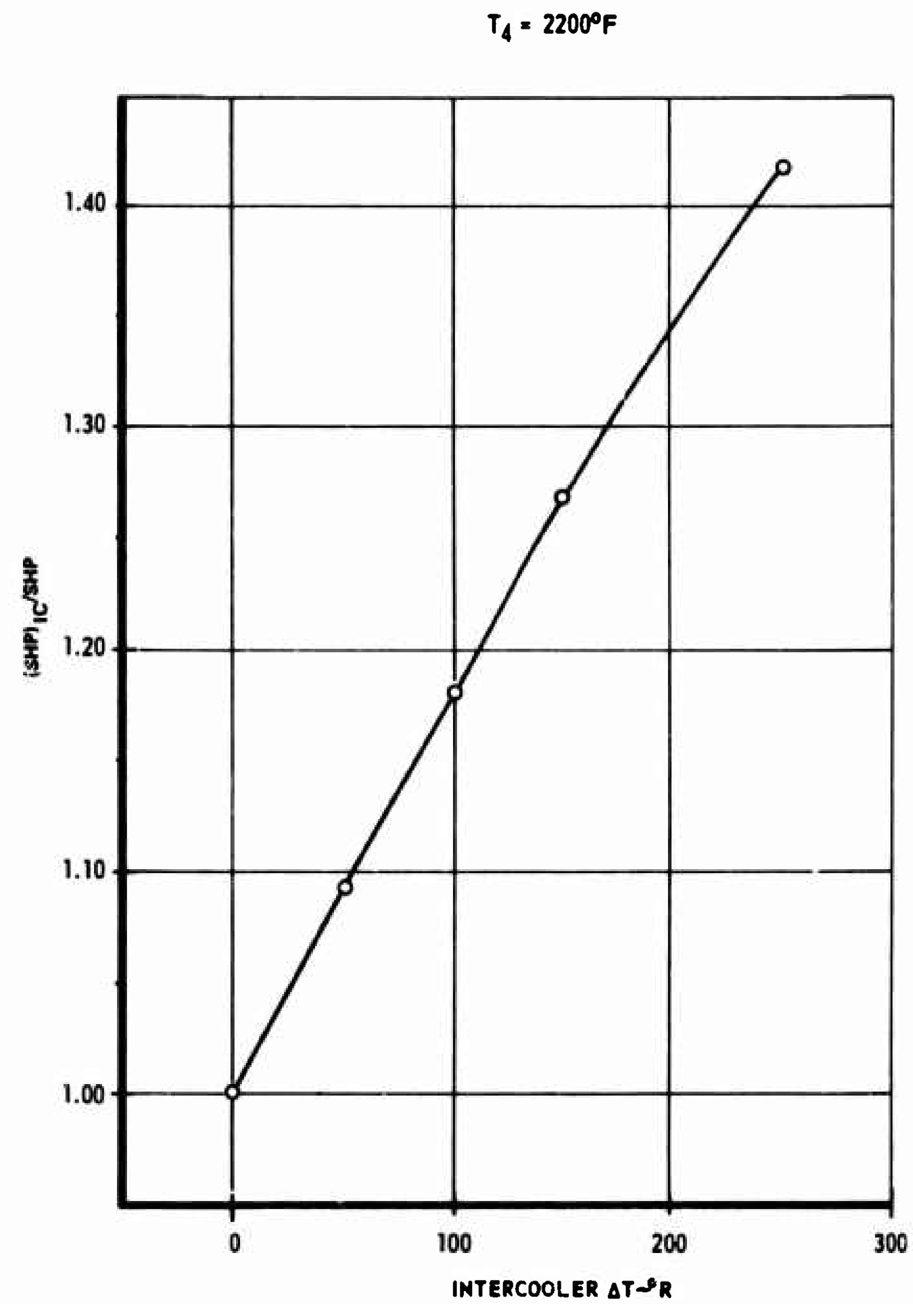

Figure 31. The effect of compressor intercooling on the power augmentation ratio of a non-regenerative engine with variable area power turbine, 6000 feet static, T ambient = 95°F.

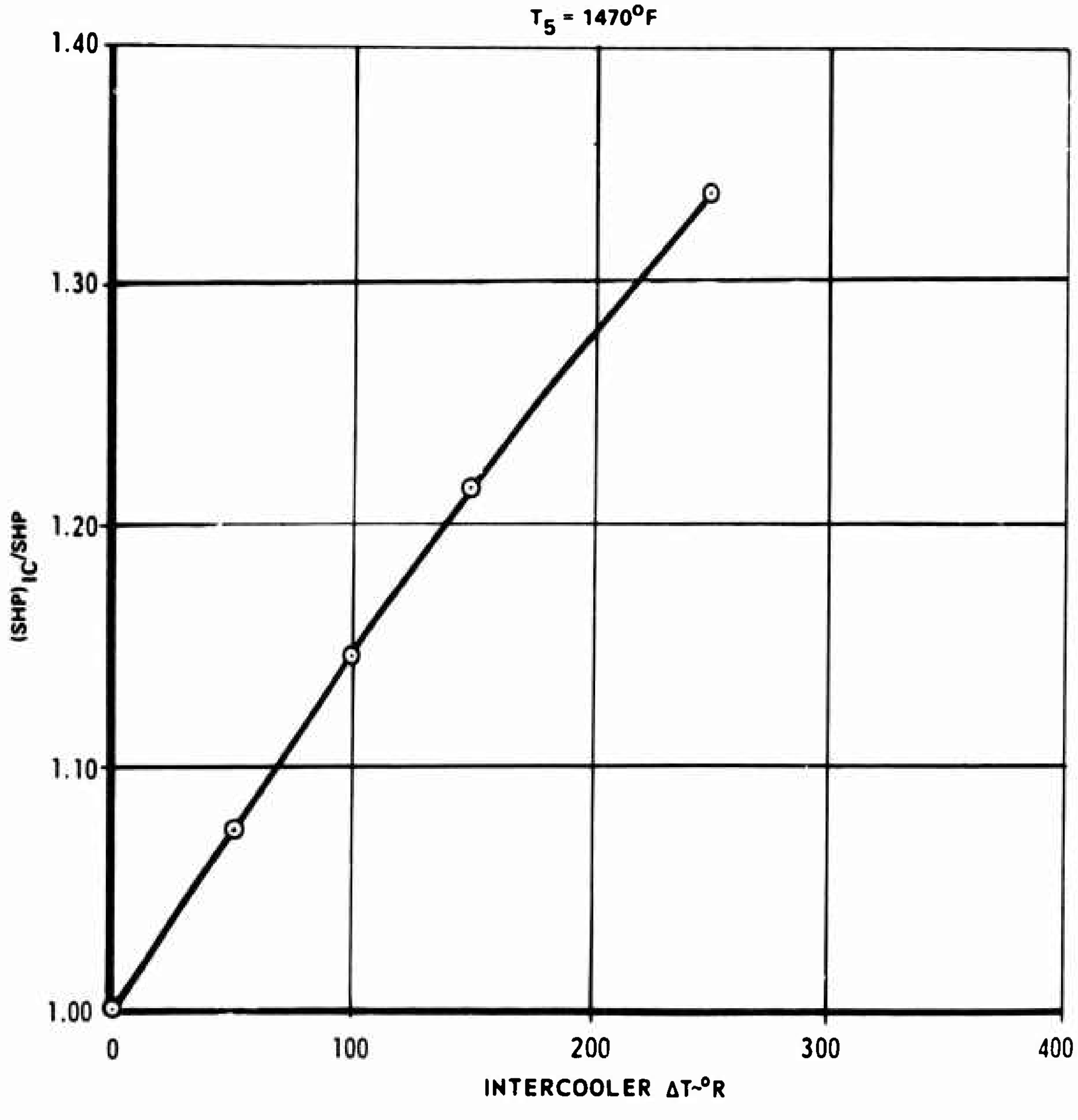

Figure 32. The effect of compressor intercooling on the power augmentation ratio of a non-regenerative engine with variable area power turbine, 6000 feet static, T ambient = 95°F.

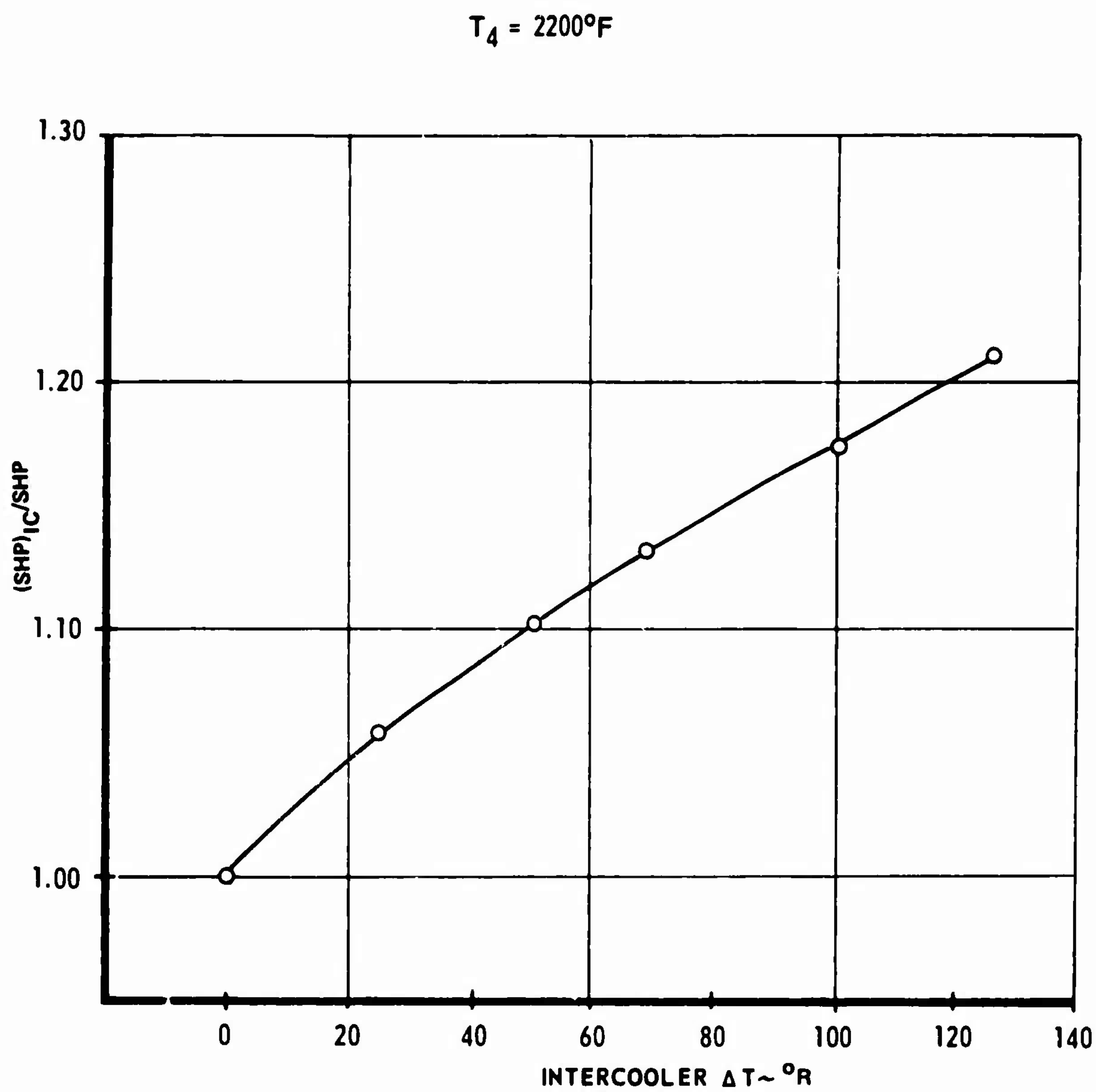

Figure 33. The effect of compressor intercooling on the power augmentation ratio of a non-regenerative engine with constant area power turbine, 6000 feet static, T ambient = 95°F.

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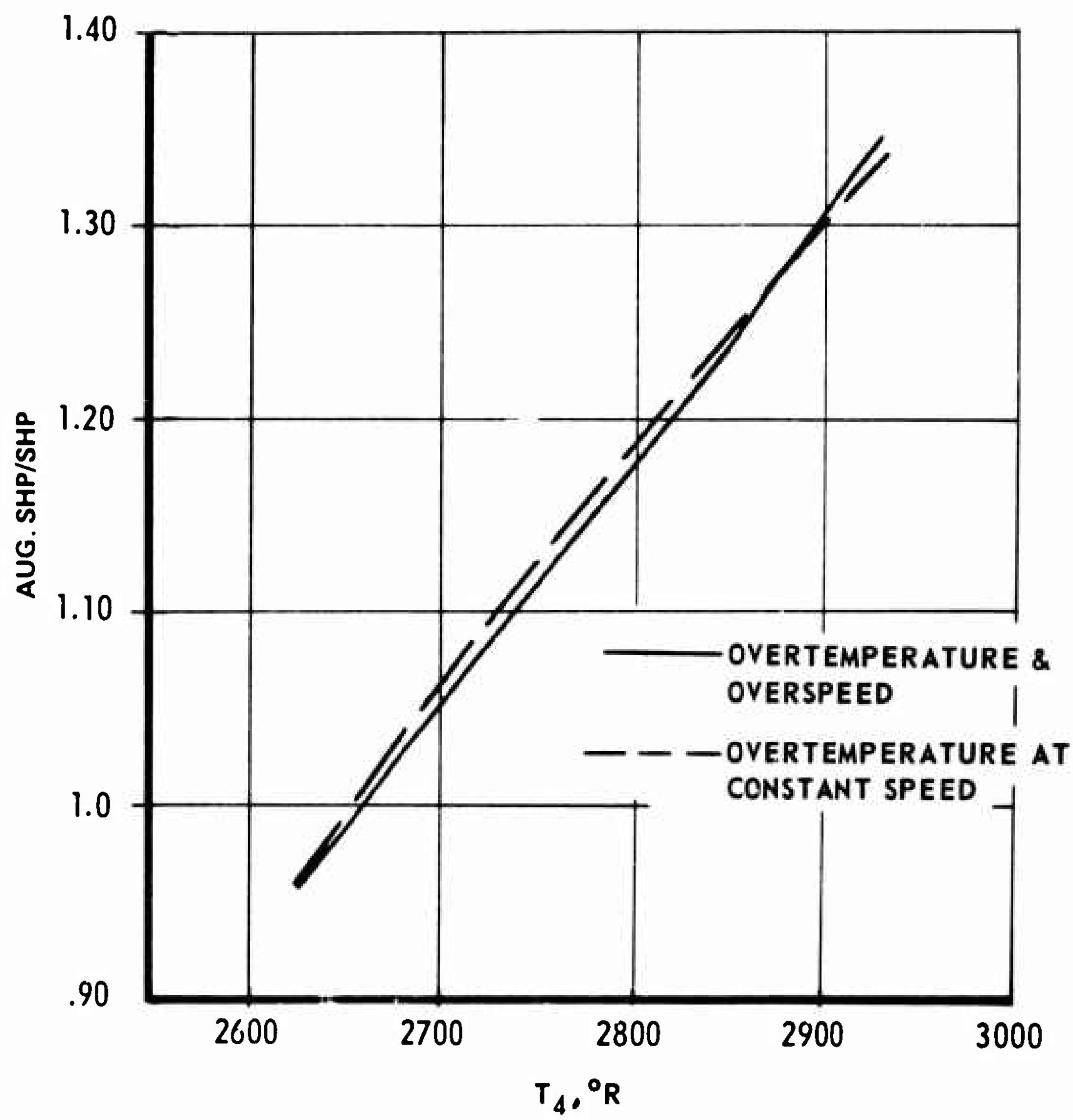


Figure 35. The effect of gas generator turbine over temperature on the power augmentation ratio of a non-regenerative engine, 6000 feet static, T ambient = 95°F.

Similar studies made on the inter-turbine and post-turbine regenerative engines operating in the overtemperature overspeed mode only, gave results (Figures 36 and 37) that were approximately the same as those for the non-regenerative engines.

Of the several possible approaches which could be used in designing a system to allow operation at the high temperature levels shown, the method studied used a heat exchanger cooled by engine fuel to cool all of the turbine and combustor cooling air before its use.

Combined Turbine Overtemperature and Compressor Inlet Water Injection

By combining compressor inlet water injection with turbine overtemperature, the desired augmentation ratio of 1.43 can be achieved at lower temperature and lower water consumption that can be achieved by using either system separately (Figure 38). By matching the amount of water injected and the amount of increase in temperature in such a way that the reduction in compressor discharge temperature gives the cooling effectiveness required with the increased temperature, the need for an auxiliary cooling means can be eliminated. For the non-regenerative engine, these values were a T_4 of 2775°R and a water/air ratio of .017; for the post-turbine regenerative engine the values were a T_4 of 2760°R and a water/air ratio of .015.

Interburning

The interburner was studied only for the non-regenerative enigne, as it had the lowest gas generator turbine exit temperature and therefore could accommodate the largest temperature rise in the burner. Calculations were made for 0, 2.8, and 4 percent power turbine cooling air over interburner temperature rise ranges of 400° and 600°R. The results shown in Figure 39 give a maximum augmentation of 19 percent for the uncooled power turbine. Performance of the cooled power turbines was calculated for temperature rises up to 600°R. For 2.8 percent cooling air, the maximum augmentation was 23 percent, for 4 percent cooling air, it was only 16 percent. These results show that the cooled turbine does not have sufficient advantage over the uncooled turbine to warrant its consideration.

One way of eliminating the need for use of a variable-area power turbine when interburning is by combining intercooling and interburning, carefully matched to provide equal but opposite changes in the power turbine inlet flow function. Engine performance results for the non-regenerative engine using this method are shown on Figure 40. They gave a maximum augmentation ratio of 54 percent, but maximum power output with all losses included was only 1610 SHP, 94 horsepower lower than the sea level static standard day value.

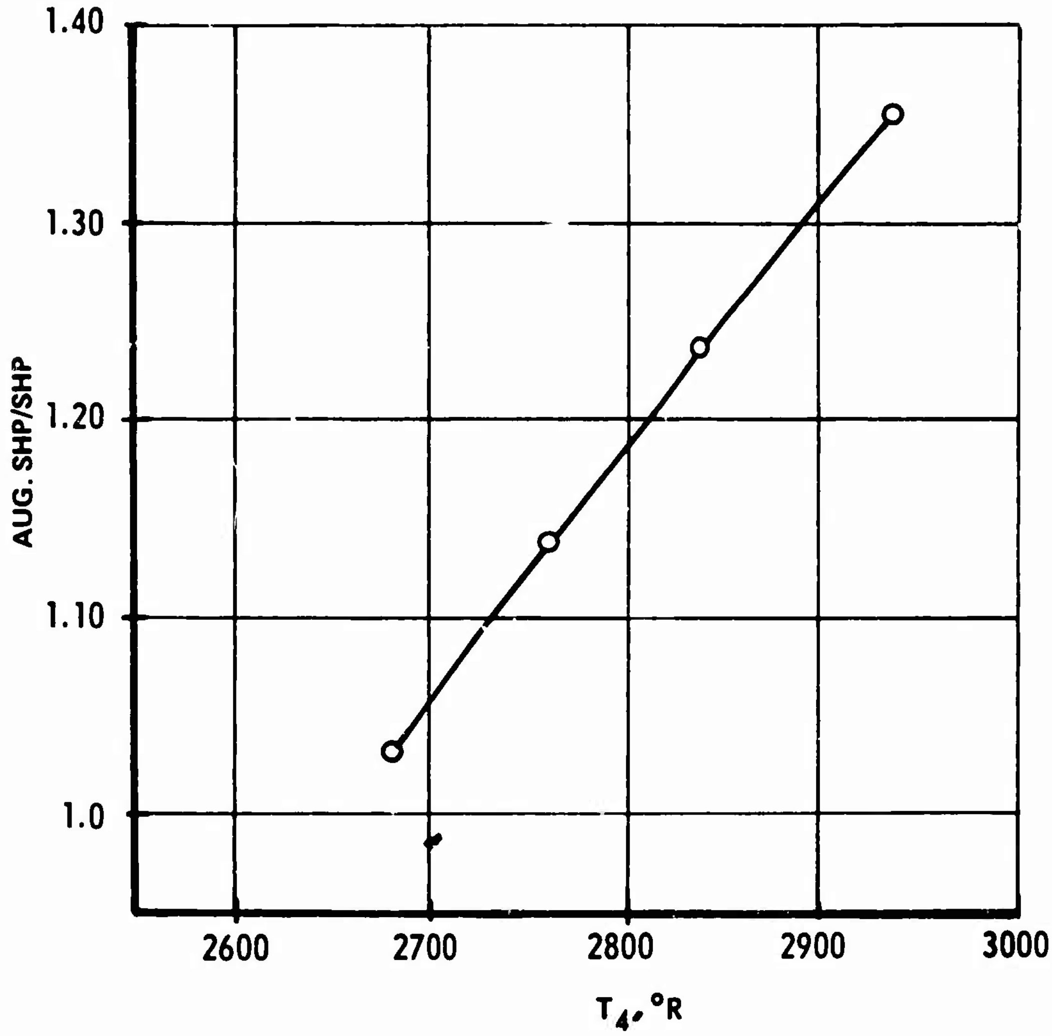


Figure 36. The effect of gas generator turbine over temperature and over speed on the power augmentation ratio of an inter-turbine regenerative engine, 6000 feet static, T ambient = 95°F

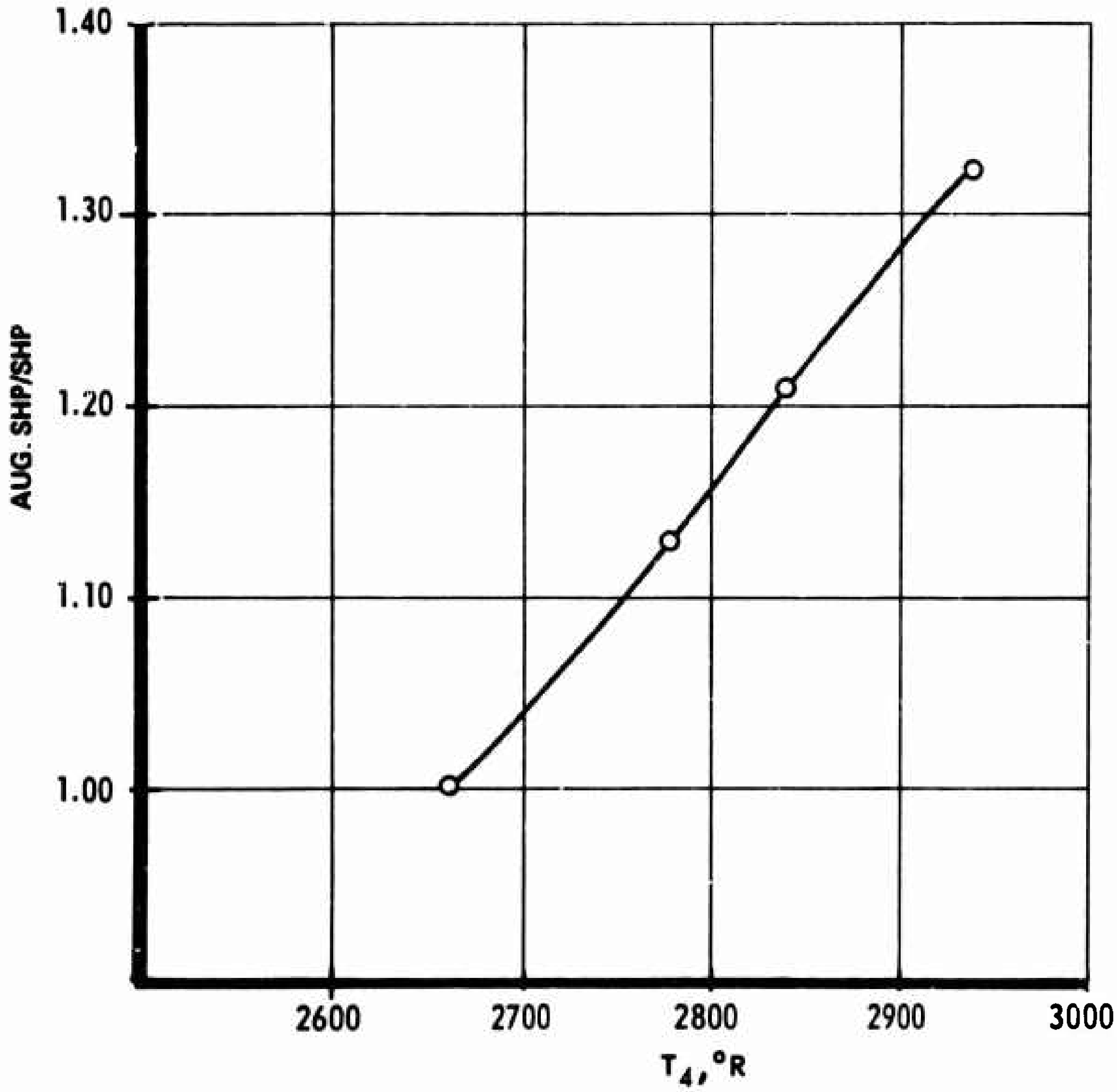


Figure 37. The effect of gas generator turbine over temperature and over speed on the power augmentation ratio of a post-turbine regenerative engine, 6000 feet static, T ambient = 95°F.

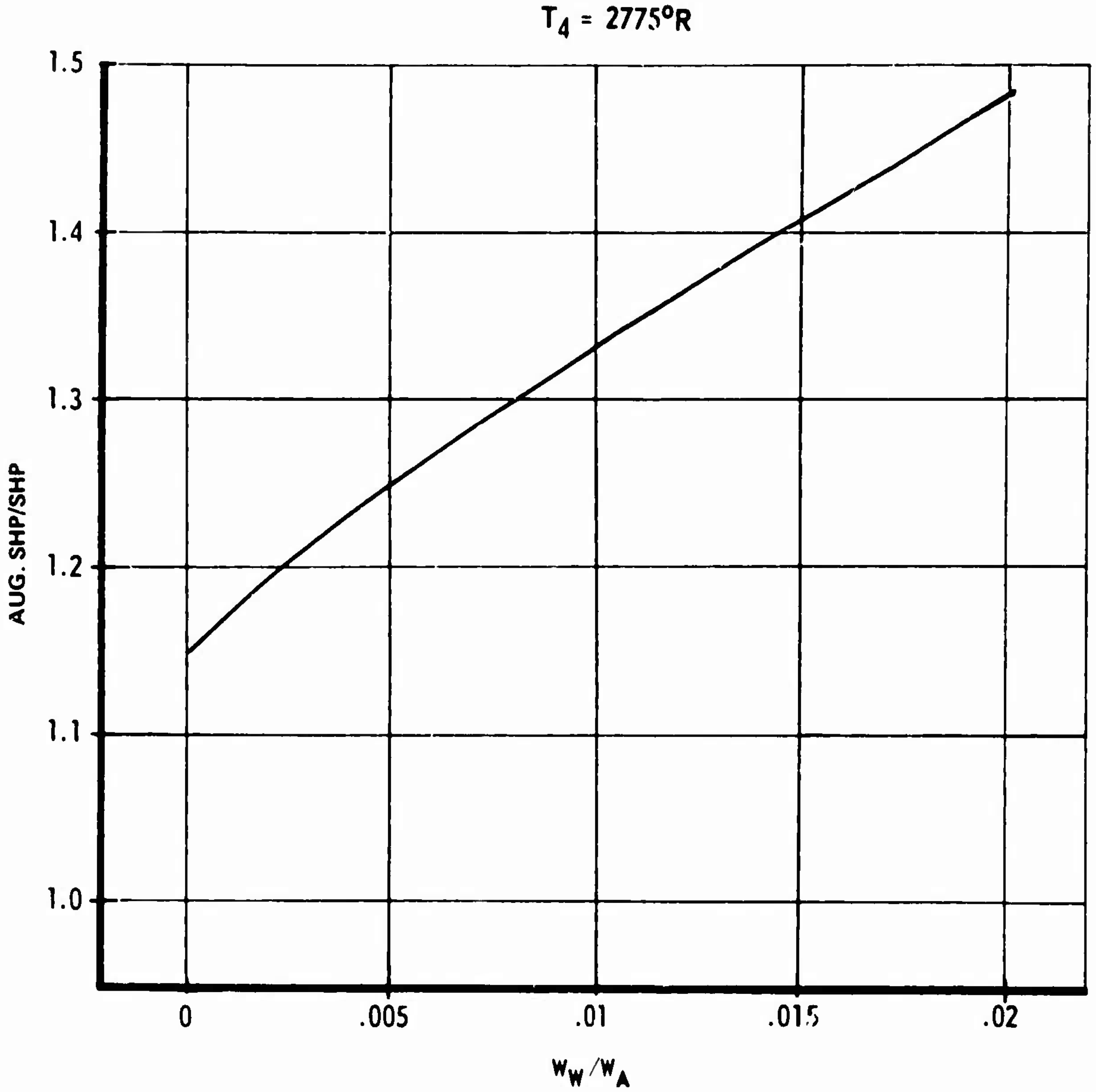


Figure 38. The combined effect of compressor water injection and gas generator turbine over temperature on the augmentation ratio of a non-regenerative engine,6000 feet static,T ambient = 95°F.

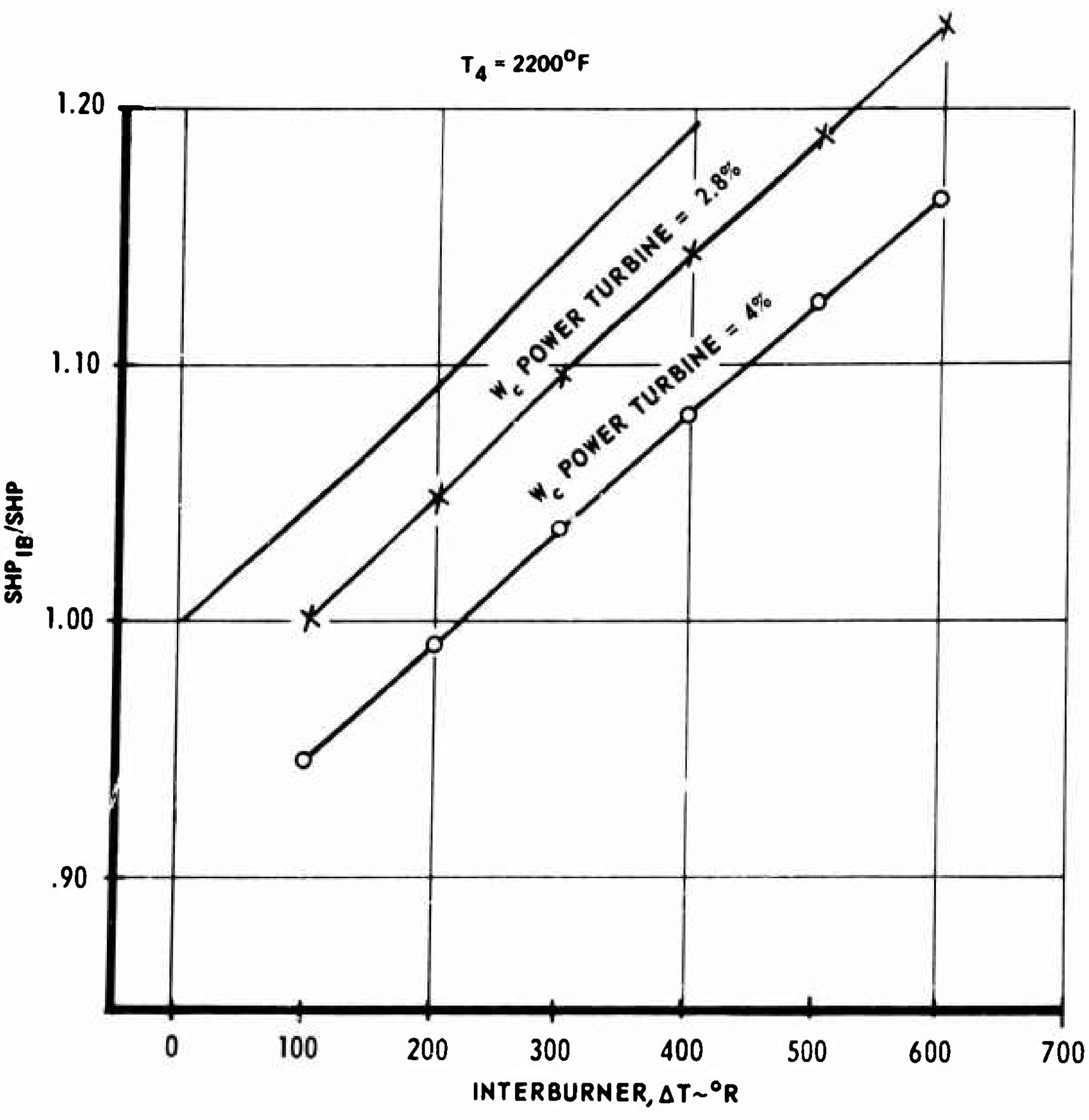


Figure 39. The effect of interburning on the power augmentation ratio of a non-regenerative engine,6000 feet static,T ambient = 95°F.

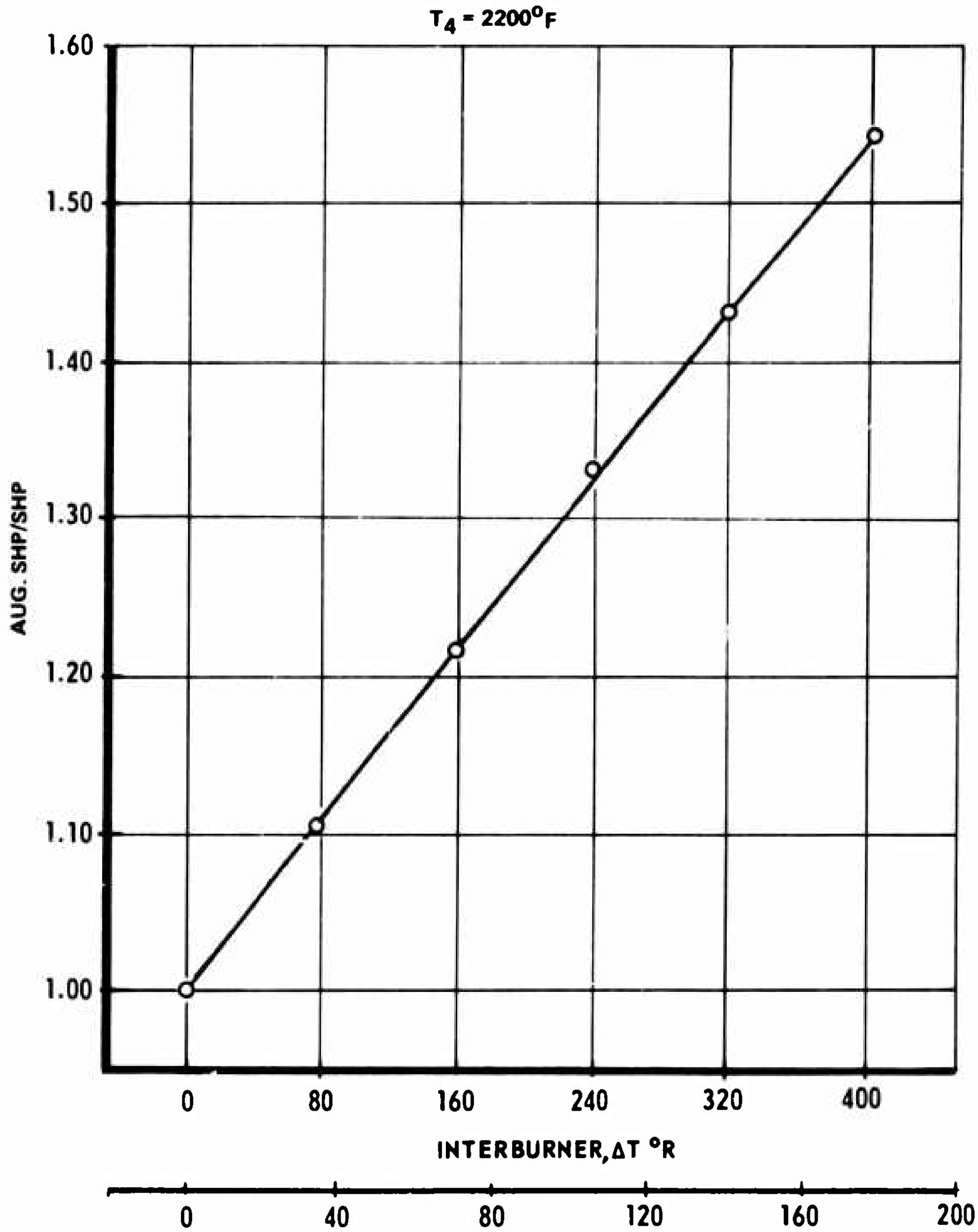


Figure 40. The effect of combined compressor intercooling and interburning on the power augmentation ratio of a non-regenerative engine with constant area power turbine, 6000 feet static, T ambient = 95°F.

RESULTS OF EMERGENCY POWER AUGMENTATION CALCULATIONS

Simple Augmentation Systems

The emergency power augmentation methods were evaluated first on an individual or simple combination basis to determine the limits of their potential. The evaluation was carried out at sea level static standard day, on the engines designed at this point. The methods evaluated were: engine overspeed combined with compressor water or water-alcohol injection, combustor ammonia injection, gas generator turbine inlet overtemperature; pre-compressor ammonia injection using a rotor lockup to hold constant gas generator rpm and T_4, and overtemperature using a rotor lockup to hold constant speed. Since the assumed compressor characteristics are the same in the operational range of this study, the results applied to all engine types.

The calculated results (Figures 41 through 44) show that the augmentation ratios with maximum values between 1.20 and 1.37 were far short of the requirements of all of the basic engines except those sized at 6000 feet, 95°F, and the inter-turbine regenerative engine sized for takeoff at sea level without bypassing. Data for the inter-turbine regenerative engine are not shown because in all cases they fell between the values obtained for the non-regenerative and post-turbine regenerative engines.

An examination of the data generated in producing these results revealed that for all of the systems except pre-compressor water or water-alcohol injection, the augmentation ratio obtainable was limited by the compressor stall or corrected speed limits.

To bypass this limit, additional degrees of freedom in controlling the compressor operating point were provided by incorporating a variable-area gas generator turbine into each basic engine studied, while at the same time varying the effective power turbine area by geometry changes or by injection of hot gases into the power turbine.

Combined Turbine Overtemperature, Combustor Liquid Injection, and Hot Gas Injection Into the Power Turbine

A System composed of turbine inlet overtemperature, combustor liquid injection, and hot gas injection into the power turbine provided a maximum augmentation ratio of 1.51 (Figure 45) when the gas generator turbine area was opened 10 per cent and the compressor was at its corrected speed limit. The small improvement shown with injection of mass into the power turbine is due to the decreases in power turbine efficiency as the inlet area is varied to accommodate the flow increase. For computational purposes, the liquid injected into the combustor was assumed to be ammonia, and the hot gas injected was the decomposition products

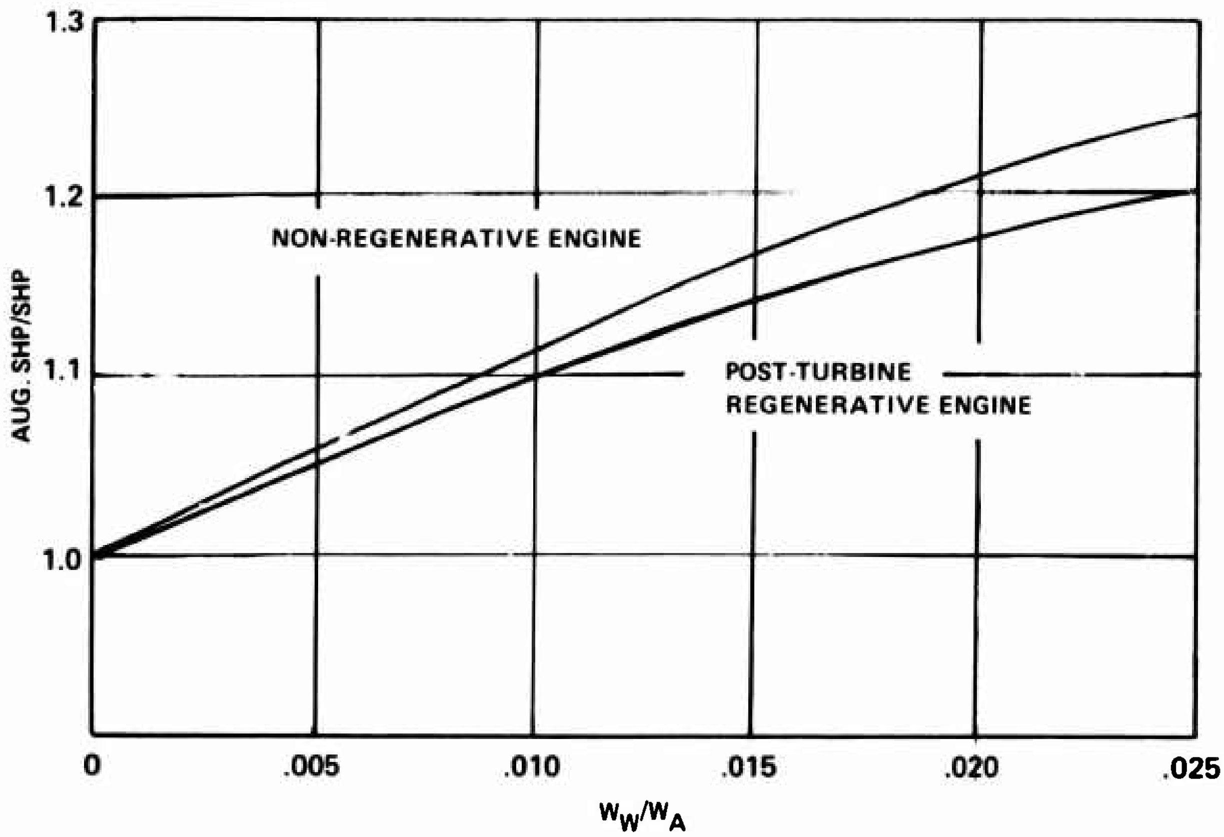


Figure 41. The effect of compressor inlet water injection on augmentation ratio, sea level static, standard day.

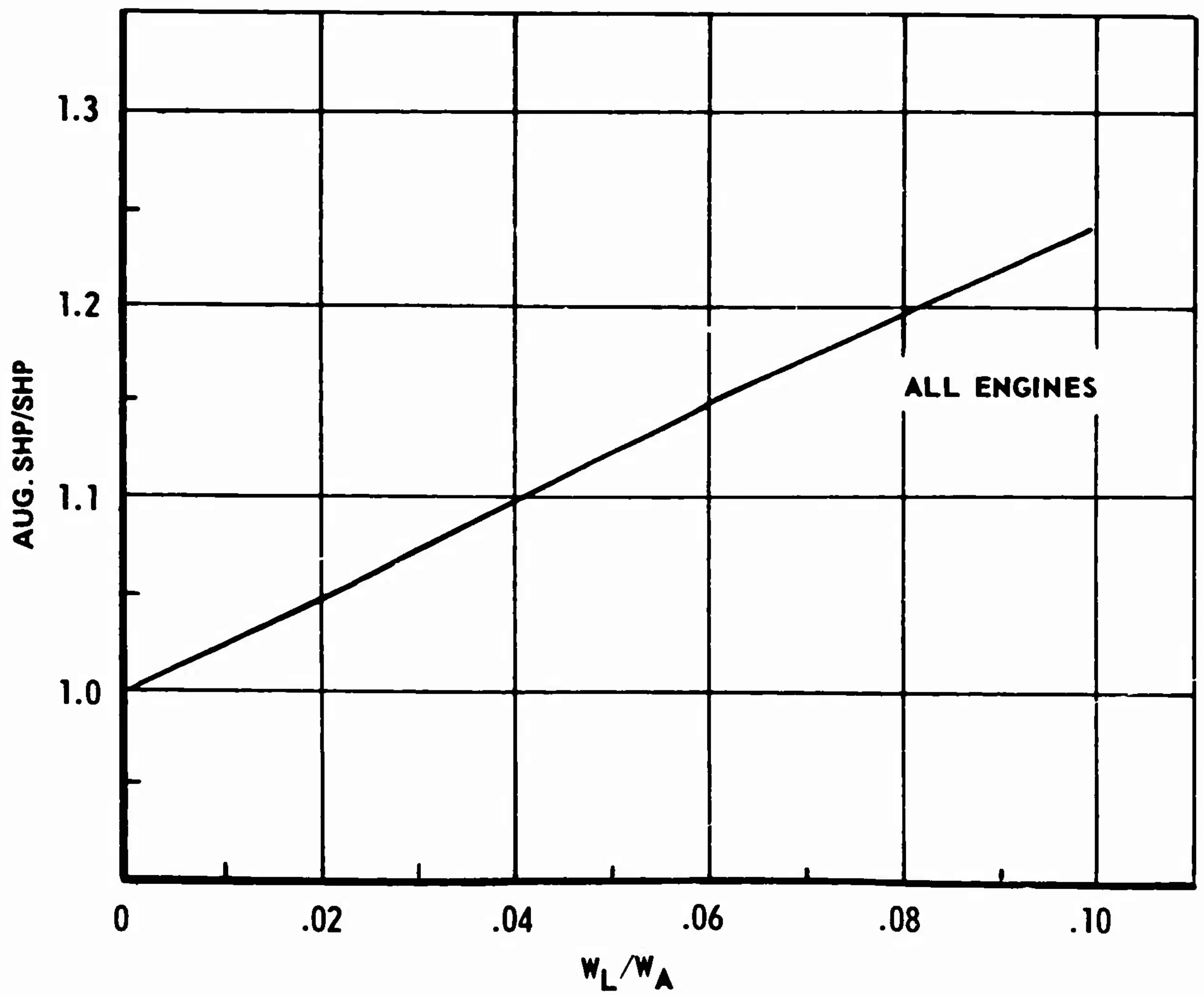


Figure 42. The effect of combustor liquid injection on augmentation ratio, sea level static, standard day.

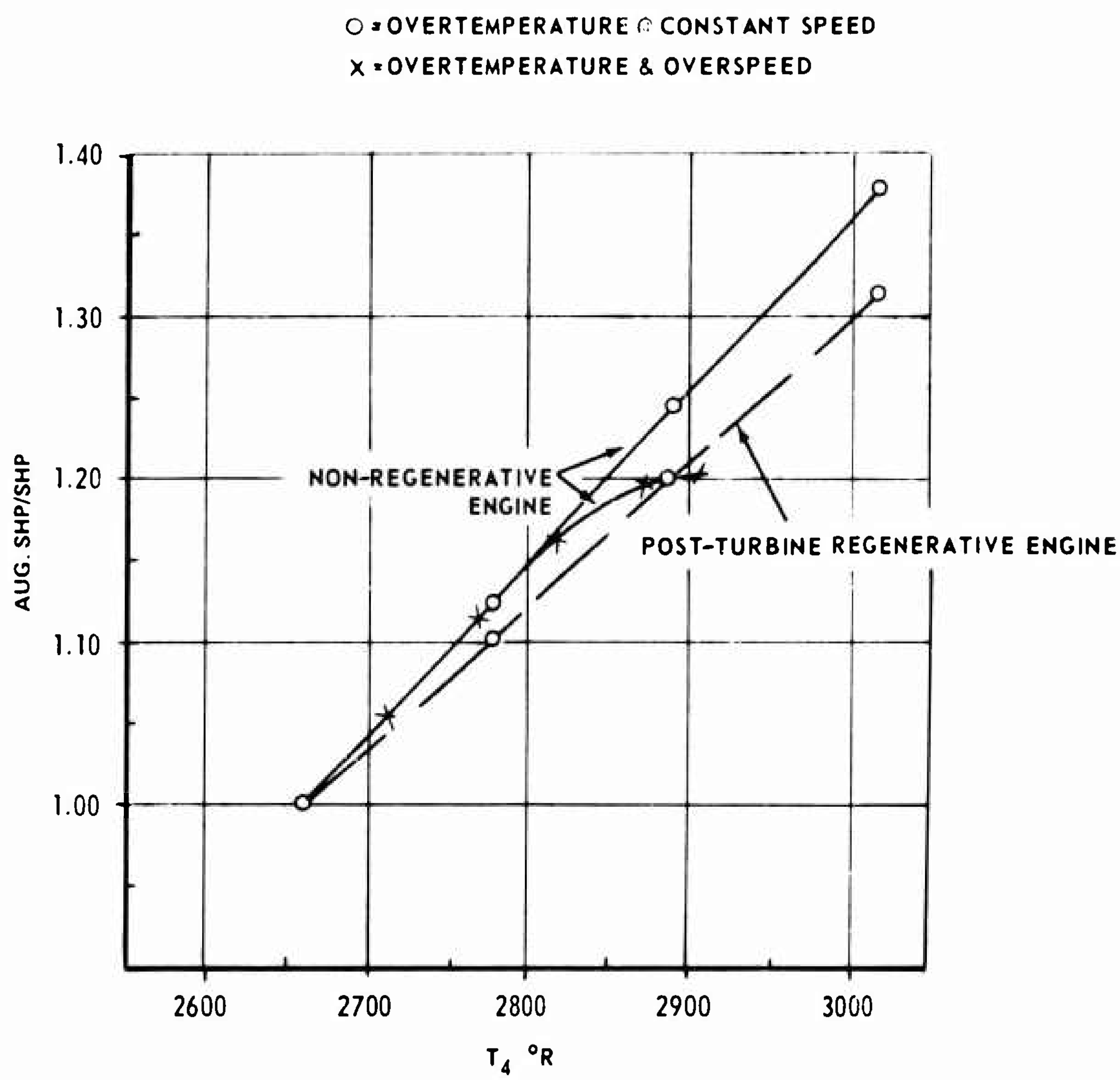


Figure 43. The effect of gas generator turbine inlet over temperature on augmentation ratio, sea level static, standard day.

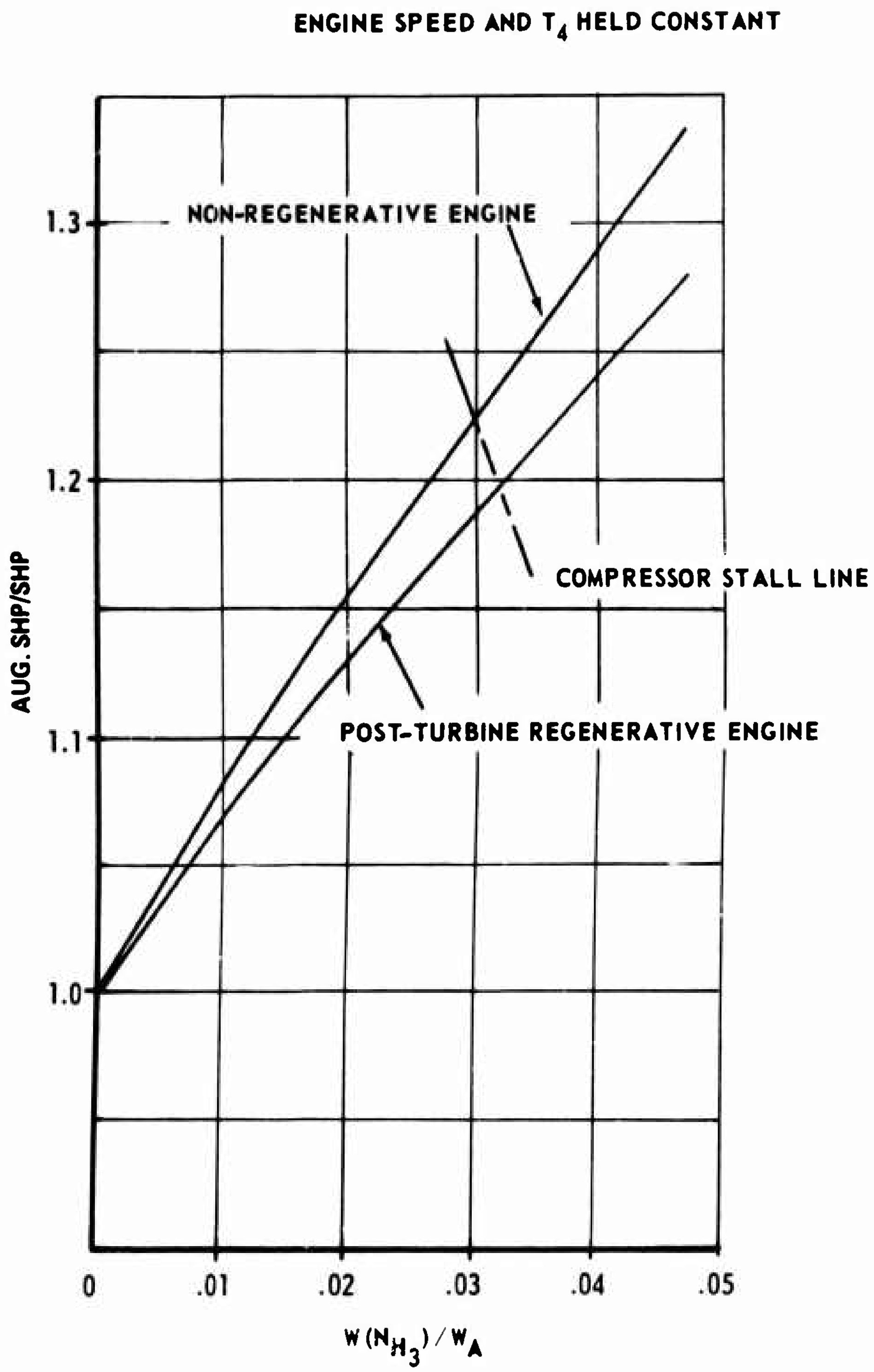


Figure 44. The effect of pre-compressor ammonia injection on augmentation ratio, sea level static, standard day.

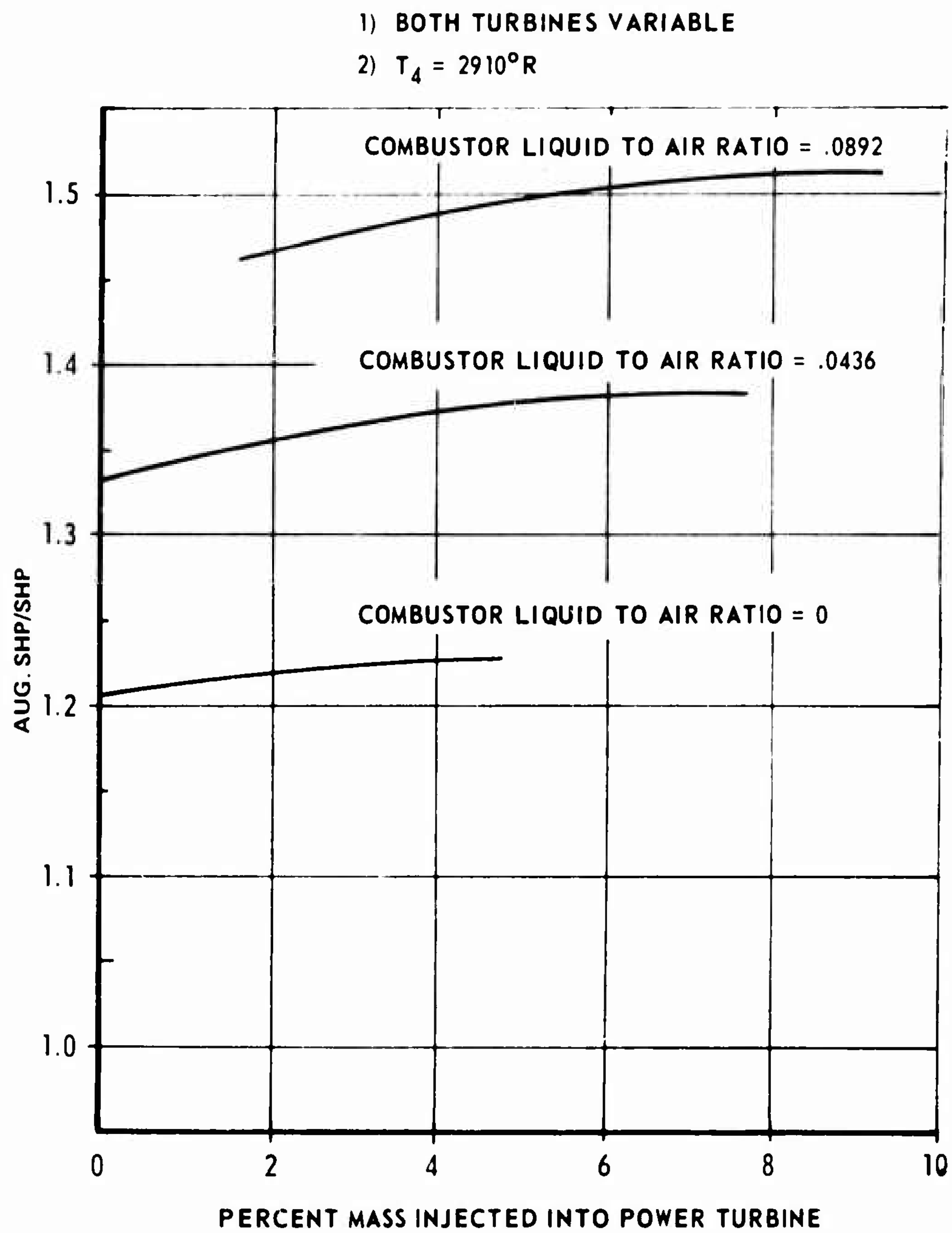


Figure 45. The combined effect of gas generator turbine over temperature, combustor liquid injection and power turbine hot gas injection on augmentation ratio, sea level static, standard day.

of hydrogen peroxide.

Combined Pre-Compressor Ammonia Injection, Combustor Liquid Injection, Turbine Overtemperature, and Hot Gas Injection Into the Power Turbine

Higher levels of augmentation were obtained by using 3 percent ammonia injected in front of the compressor, keeping the turbine inlet temperature at 2910°R, and injecting ammonia into the combustor and hydrogen peroxide or hydrazine into the power turbine. The power turbine area was not varied, and the mass injected at that point was just sufficient to fill the nominal area. The calculated results, Figure 46, show that 79 percent augmentation was possible using this method.

Combined Pre-Compressor Ammonia Injection and Turbine Overtemperature

The results obtained with this sytem applied to an engine with both turbines variable are shown on Figures 47 through 49. The maximum augmentation ratio achieved was 1.62 at an ammonia/air ratio of .05 and a turbine inlet temperature of 2920°R. The main advantage of this system over the previous one was the reduction in stored liquids required.

Substituting hot gas injection for the variable area power turbine increased the augmentation ratio obtainable to above the maximum 1.80 value required, when 14 percent hot gas was injected into the power turbine (Figures 50 through 52).

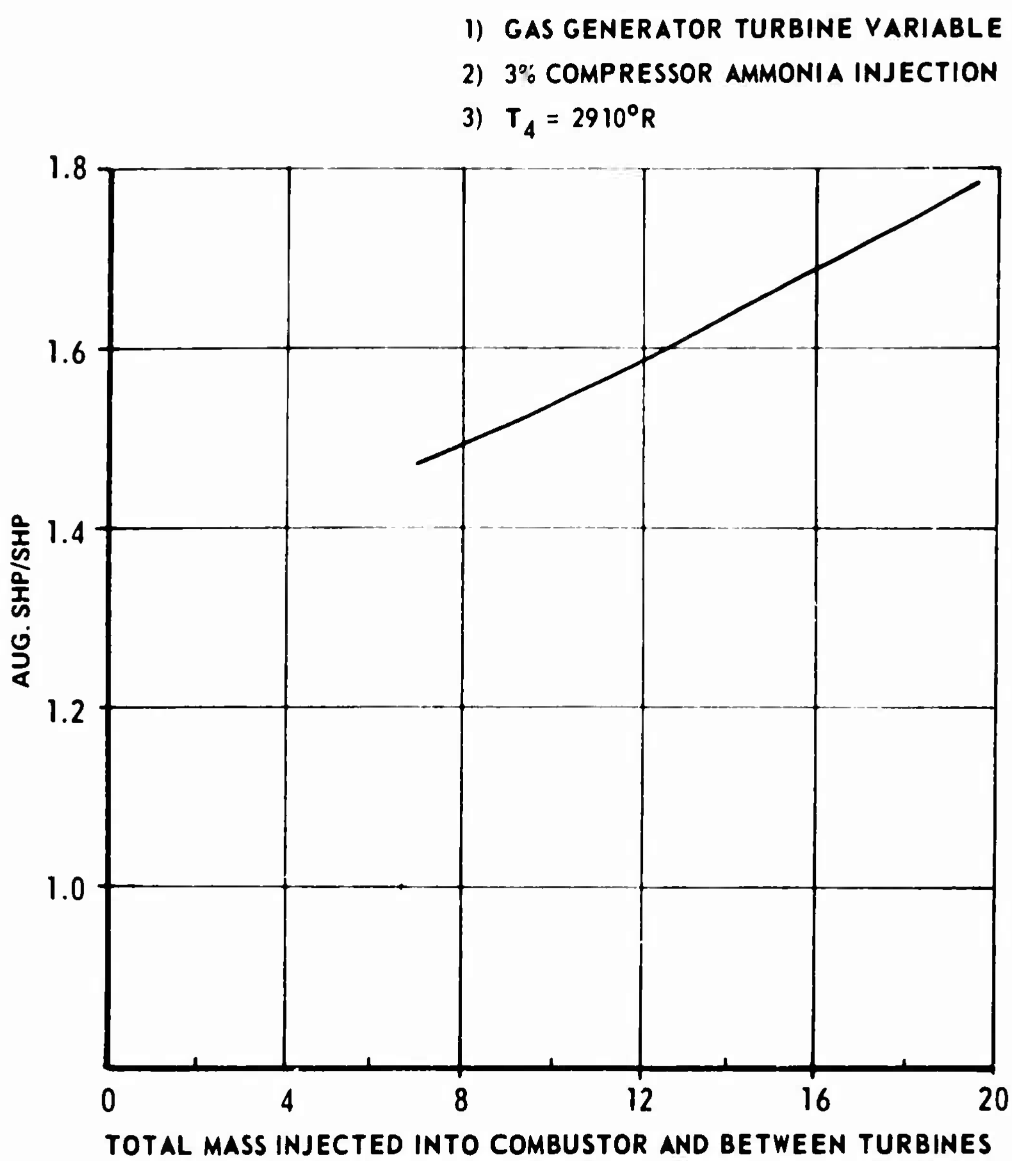


Figure 46. The combined effect of gas generator turbine over temperature, combustor liquid injection, pre-compressor liquid injection and power turbine hot gas injection on augmentation ratio, sea level static, standard day.

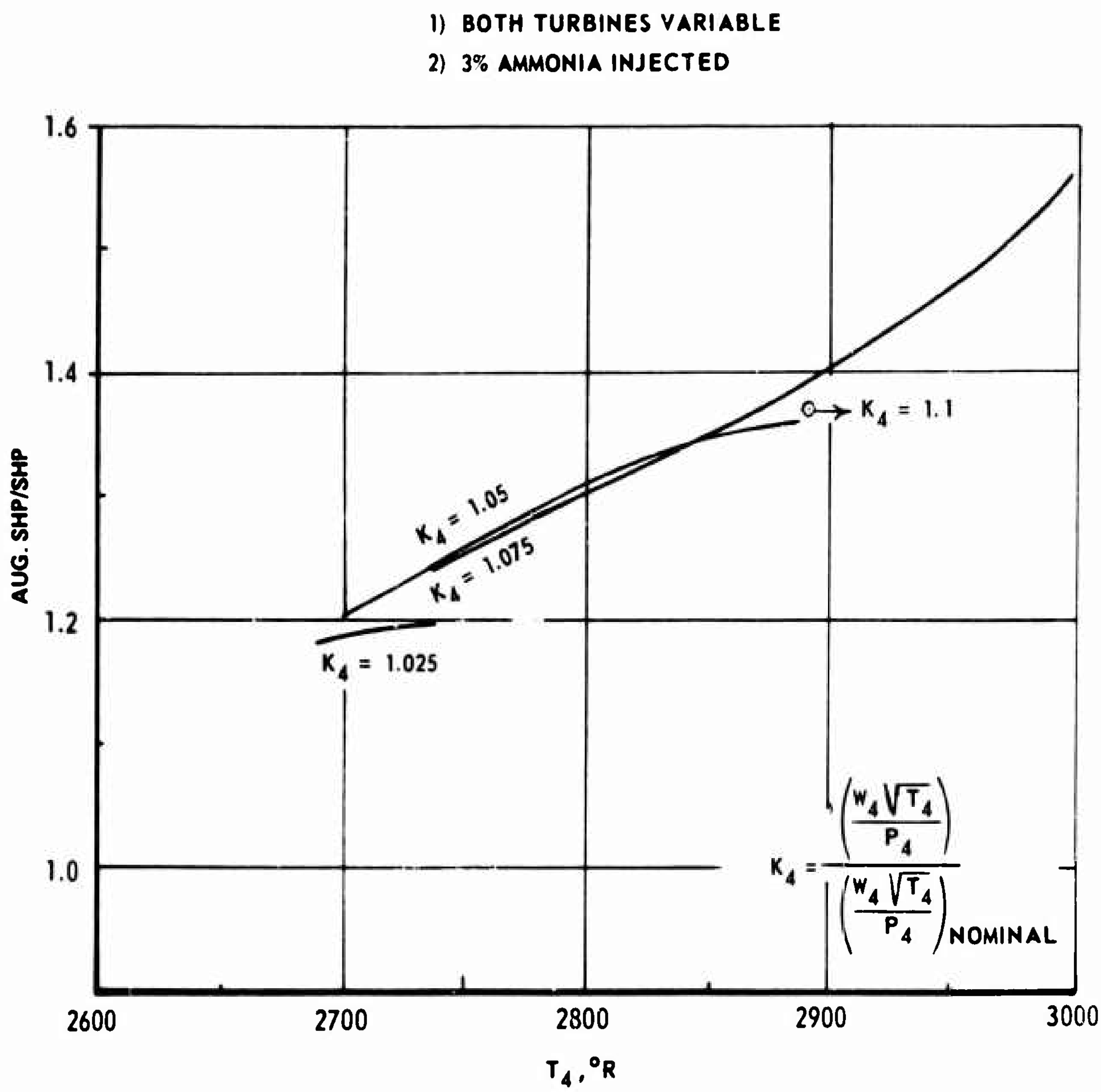


Figure 47. The combined effect of gas generator turbine over temperature and compressor inlet ammonia injection on augmentation ratio, sea level static, standard day.

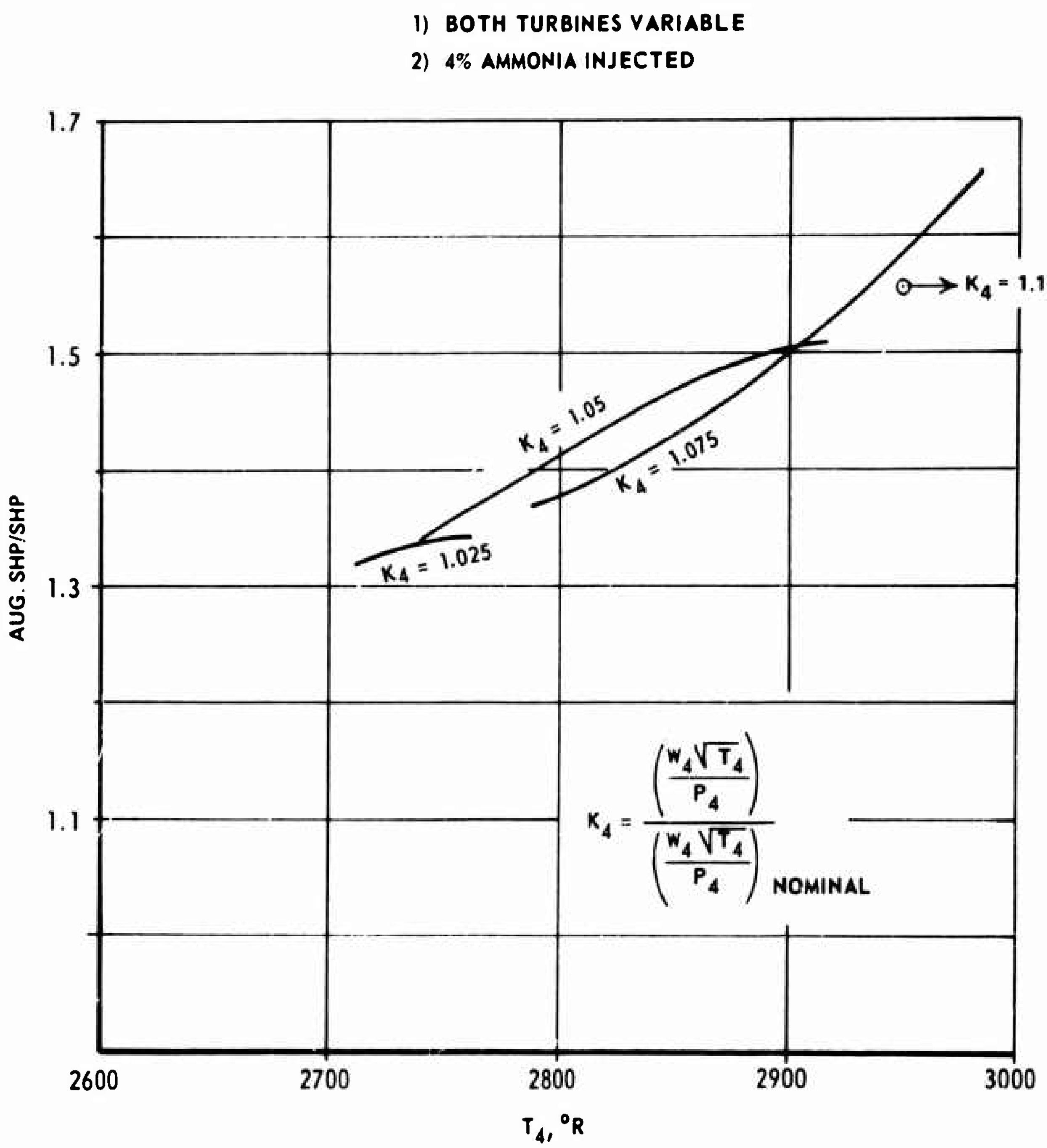


Figure 48. The combined effect of gas generator turbine over temperature and compressor inlet ammonia injection on augmentation ratio, sea level static, standard day.

1) BOTH TURBINES VARIABLE

2) 5% AMMONIA INJECTED

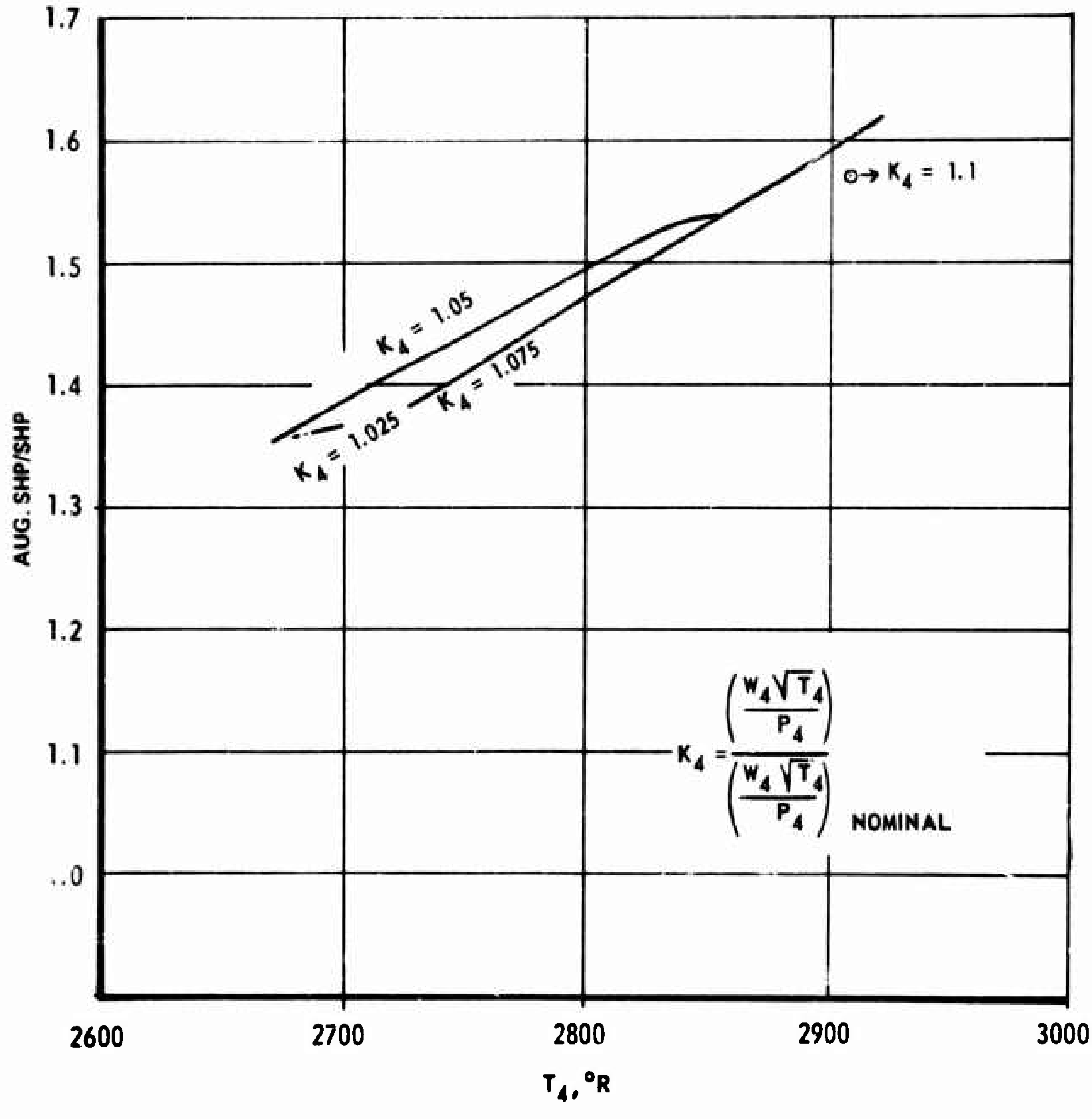


Figure 49. The combined effect of gas generator turbine over temperature and compressor inlet ammonia injection on augmentation ratio, sea level static, standard day.

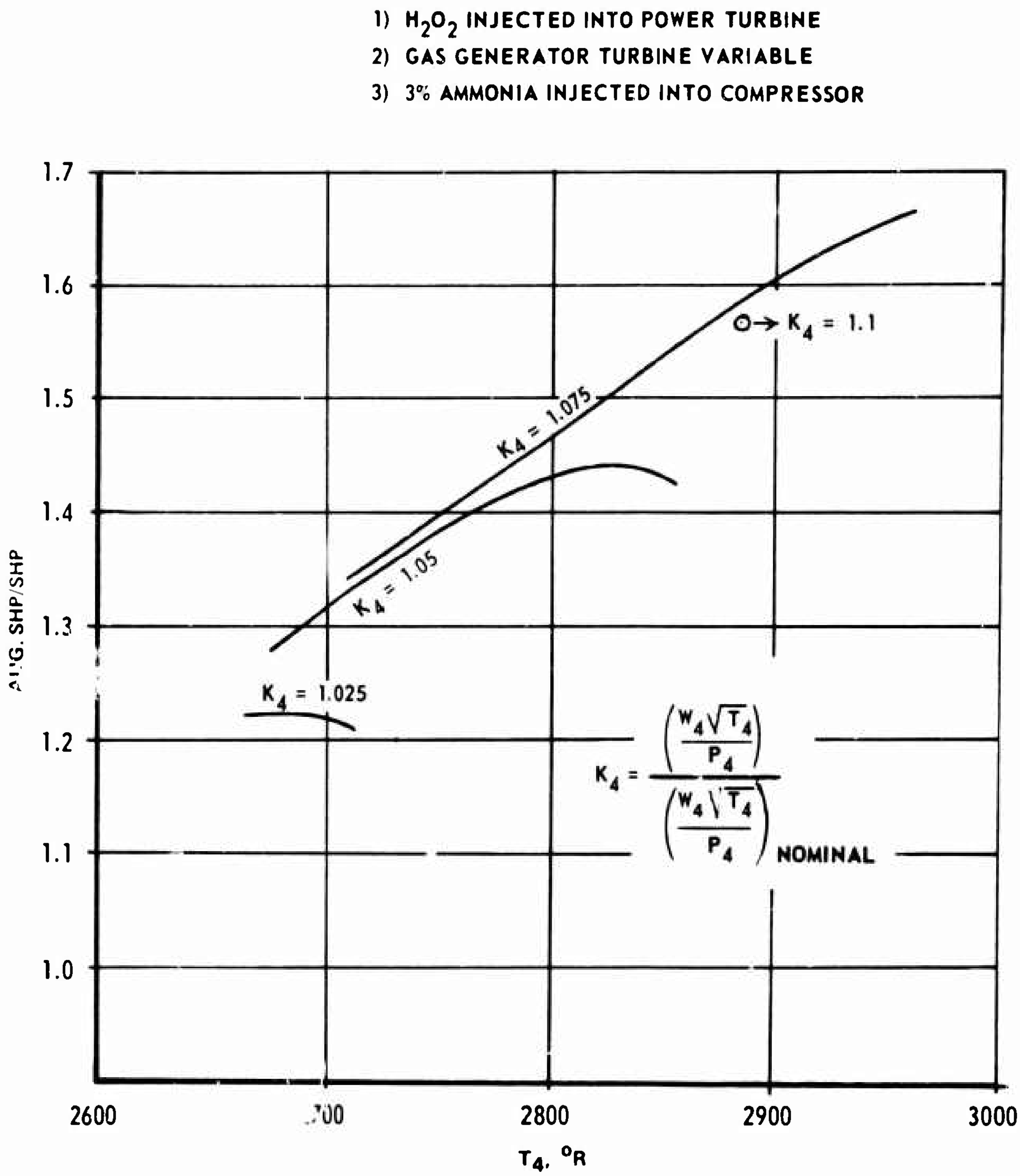


Figure 50. The combined effect of gas generator turbine over temperature, compressor inlet ammonia injection, and power turbine hot gas injection on augmentation ratio, sea level static, standard day.

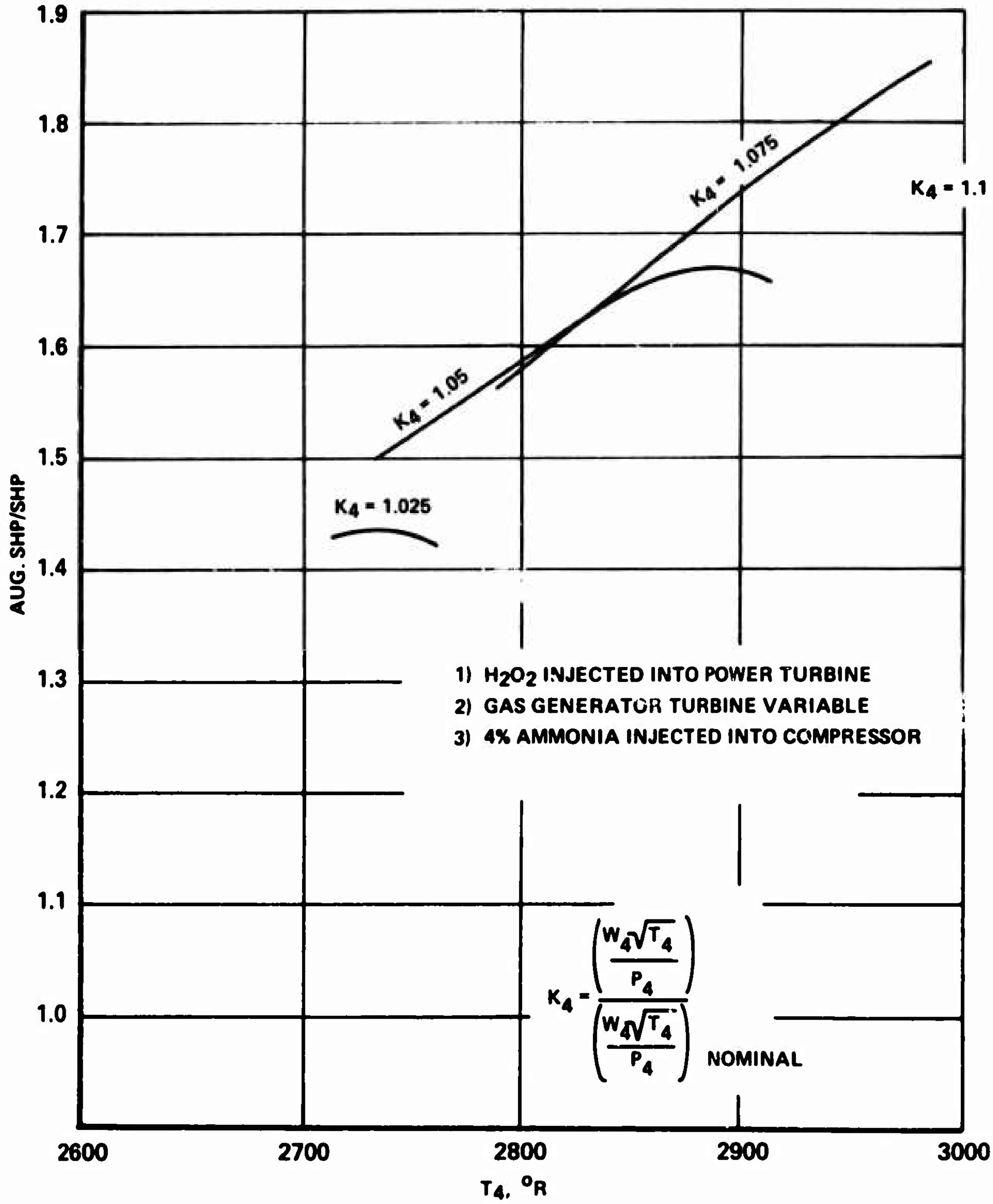


Figure 51. The combined effect of gas generator turbine over temperature, compressor inlet ammonia injection and power turbine hot gas injection on augmentation ratio, sea level static, standard day.

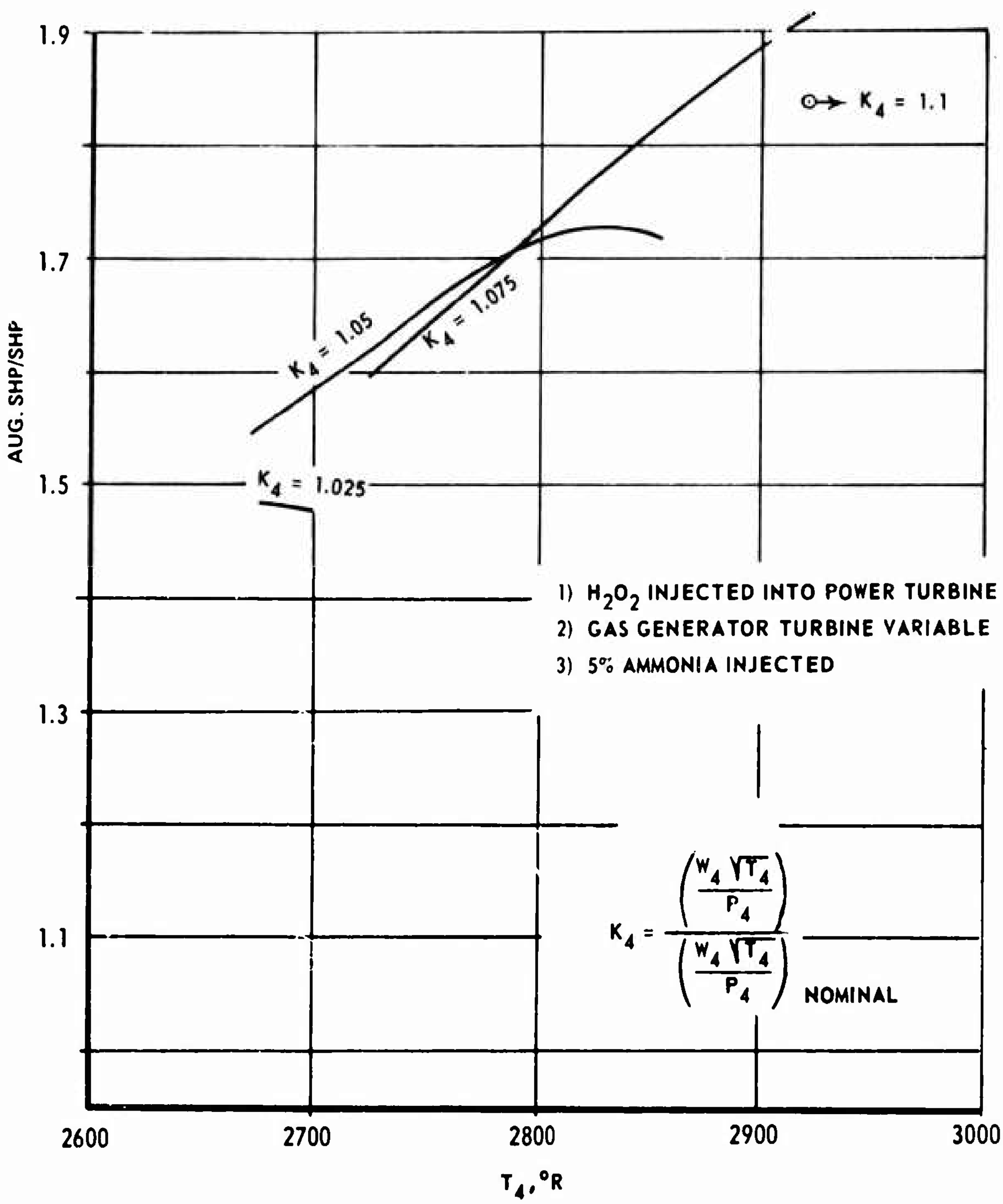


Figure 52. The combined effect of gas generator turbine over temperature, compressor inlet ammonia injection and power turbine hot gas injection on augmentation ratio, sea level static, standard day.

MECHANICAL DESIGN FEATURES OF THE AUGMENTATION SYSTEMS

WATER OR WATER-ALCOHOL INJECTION SYSTEM

The compressor inlet water injection system, shown in Figure 81 is composed of a water storage tank, a tank pressurization valve, a water injection manifold with 12 nozzles evenly distributed around the compressor inlet, a manifold control valve, and other valves, lines, and fittings required to complete the system.

When the water injection system is in use, the electrically operated tank pressurization valve is opened and the tank is pressurized from compressor discharge. The pressure rise in the tank forces the manifold control valve to open against the spring, allowing water to flow to the manifold, where it is sprayed into the compressor inlet through 12 nozzles, and signals the fuel control augmentation kit to increase fuel flow, keeping the temperature up to normal levels. When the water level in the tank drops to its low cutoff limit, the pressurization valve closes and the tank vents, reversing the sequence of operation and returning the engine to its normal operating mode. If water flow is interrupted before the low cutoff is activated, and air enters the manifold, the change is sensed by the augmentation kit and fuel flow is automatically reduced to prevent turbine overtemperature.

AMMONIA INJECTION SYSTEM

The pre-compressor ammonia injection system, Figure 53, is similar in its major components to the water injection system; but due to the differences in properties, it requires some modifications. Since ammonia has a high vapor pressure which allows it to evaporate readily even at the compressor inlet temperature, and since a maximum reduction in compressor work can be obtained by utilizing this property, the inlet to the compressor has been extended and the ammonia is injected at the front of this extended inlet to give it sufficient time to evaporate and cool the inlet air before its entry into the compressor.

The large changes in vapor pressure and liquid density with ambient temperature require changes in the tank and delivery system. First, the ammonia system must be a closed rather than a vented system to prevent boil-off of the ammonia from the tank. Second, to ensure a stable delivery rate and to prevent boiling in the delivery lines, tank pressure sould be held constant, at a value as high as the vapor pressure at the maximum design temperature. To accomplish this, the tank will be pressurized through a regulator set at 450 psi from a 2500-psi nitrogen bottle. As a safety measure to prevent rupture of the tank if its temperature exceeds 150°F, the tank must be equipped with a safety relief valve set to vent at 500 psi.

With this sytem, it is necessary to relocated the system initiation valve from the top of the tank to a position between the tank and the manifold control valve to

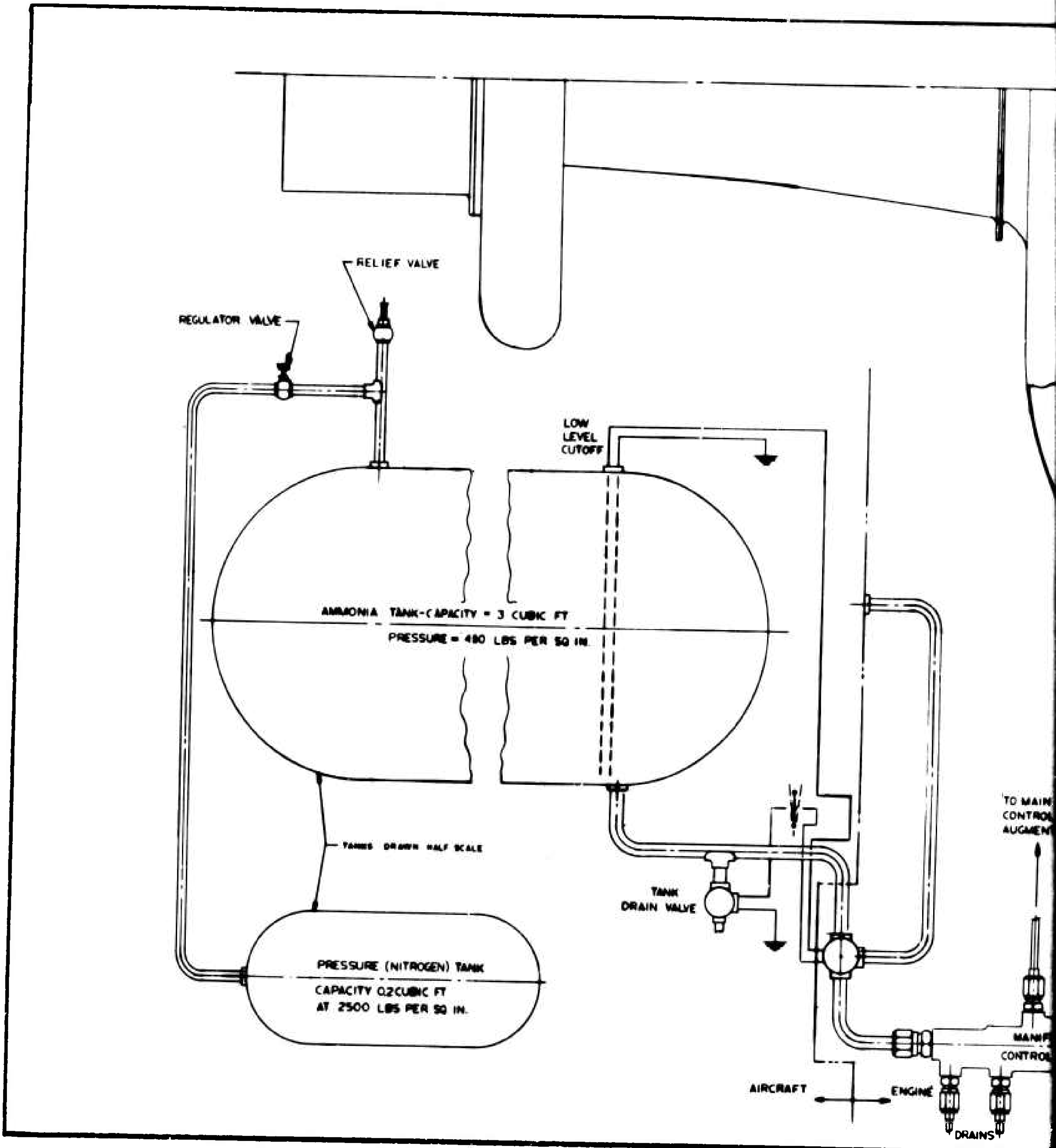
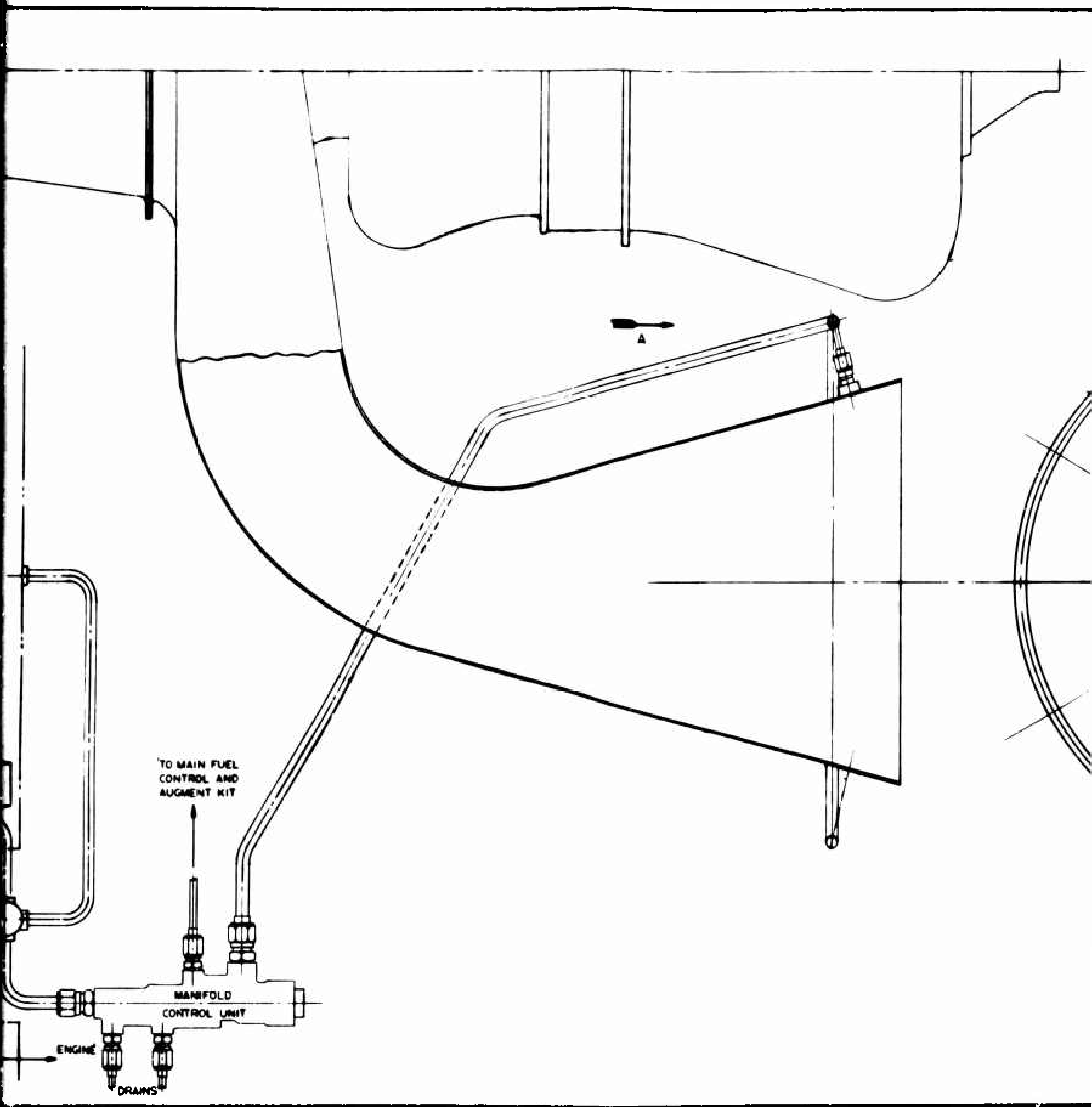
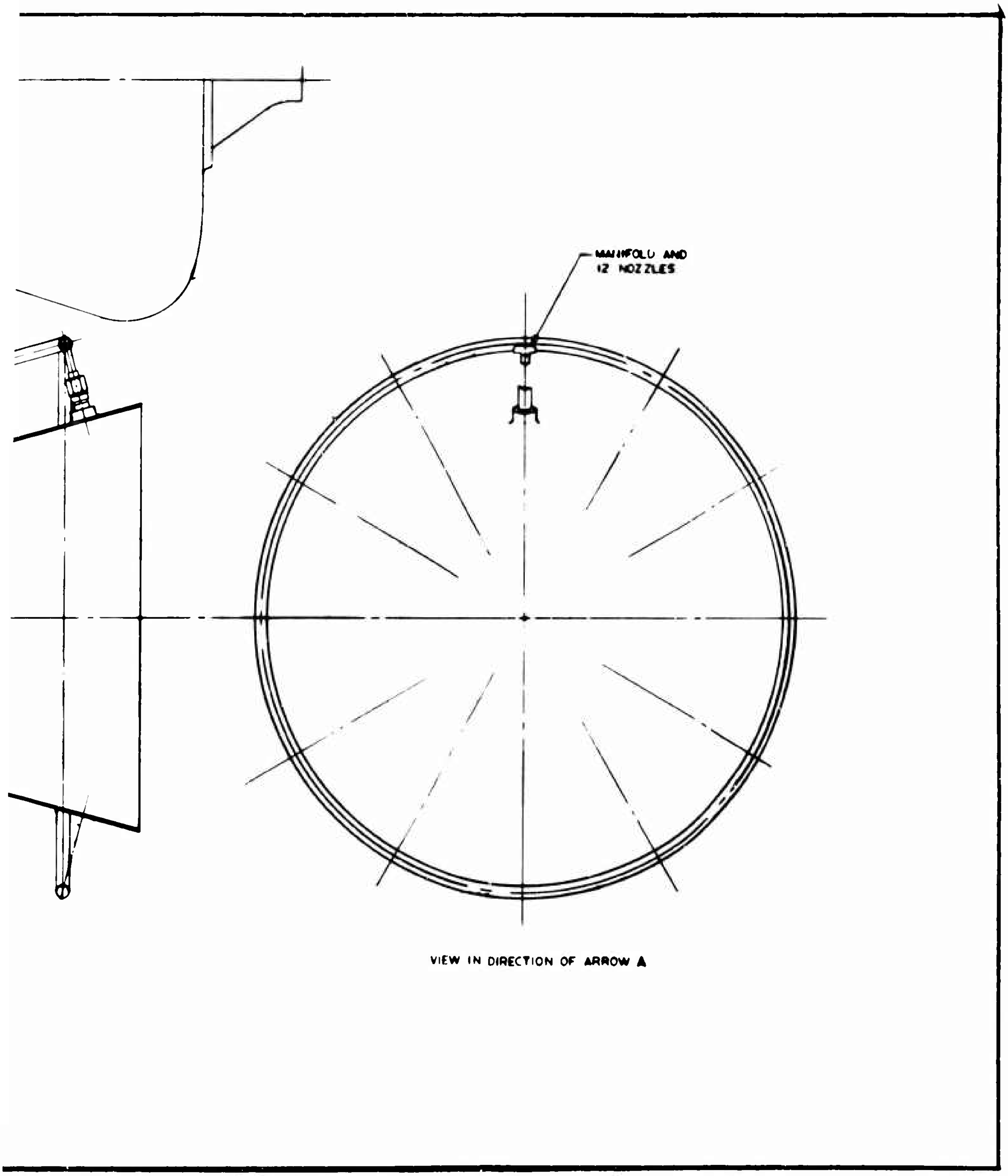


Figure 53. Typical non-regenerative engine with ammonia injection system.


A
TO MAIN FUEL CONTROL AND AUGMENT KIT
MANIFOLD CONTROL UNIT
ENGINE
DRAINS

b



VIEW IN DIRECTION OF ARROW A

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allow initiation and termination in the same manner as used for the water injection system. Except for these changes and the size difference, the systems are the same.

COMPRESSOR INTERCOOLER

Figure 54 shows the non-regenerative engine rearranged to incorporate a compressor intercooler. The high-pressure-ratio compressor was moved from its original position to the other end of the gas generator. With this arrangement, the two intercoolers have been incorporated into the engine in the position originally occupied by the high-pressure ducting that went from the compressor to the combustor.

The intercooler design consists of two shell and tube exchangers 6.25 inches in diameter by 39 inches long containing 1590 flattened tubes arranged as shown on Figure 54. Air flows through the tubes and water into the free space in the shell, where it boils and exhausts out the vent located on top of the shell. The remaining components required to complete the system are a water storage tank, a tank pressurization system, a flow-regulating valve, and distribution lines from the tank to the cooler.

When in operation, the storage tank is pressurized by compressor interstage bleed; as the pressure rises in the tank, the flow regulator opens, allowing water to flow to the intercooler. Initially, the water flow rate should be high to fill the free space in the cooler; but once the cooler is filled, the rate should be reduced to the .44 pound/second steady-state rate which is required to replace the water which has boiled away. This can be accomplished by the use of a two-position flow regulator which goes full-open until a liquid level sensor in the shell signals it to close to its low-flow position, where it would remain until operation of the system terminated. Termination of the system operation and adjustment in the fuel flow required to keep the turbine inlet temperature at its military rating would be accomplished by using the augmentation kit and sensor arrangement described for the water injection system.

COMBUSTOR INJECTION SYSTEM

The combustor liquid injection system performs basically the same functions as the compressor liquid injection system, with the major difference being that high pressures would be required in the system to overcome the pressure in the combustor; for a water-alcohol system, this could be either a pump or a high-pressure gas source.

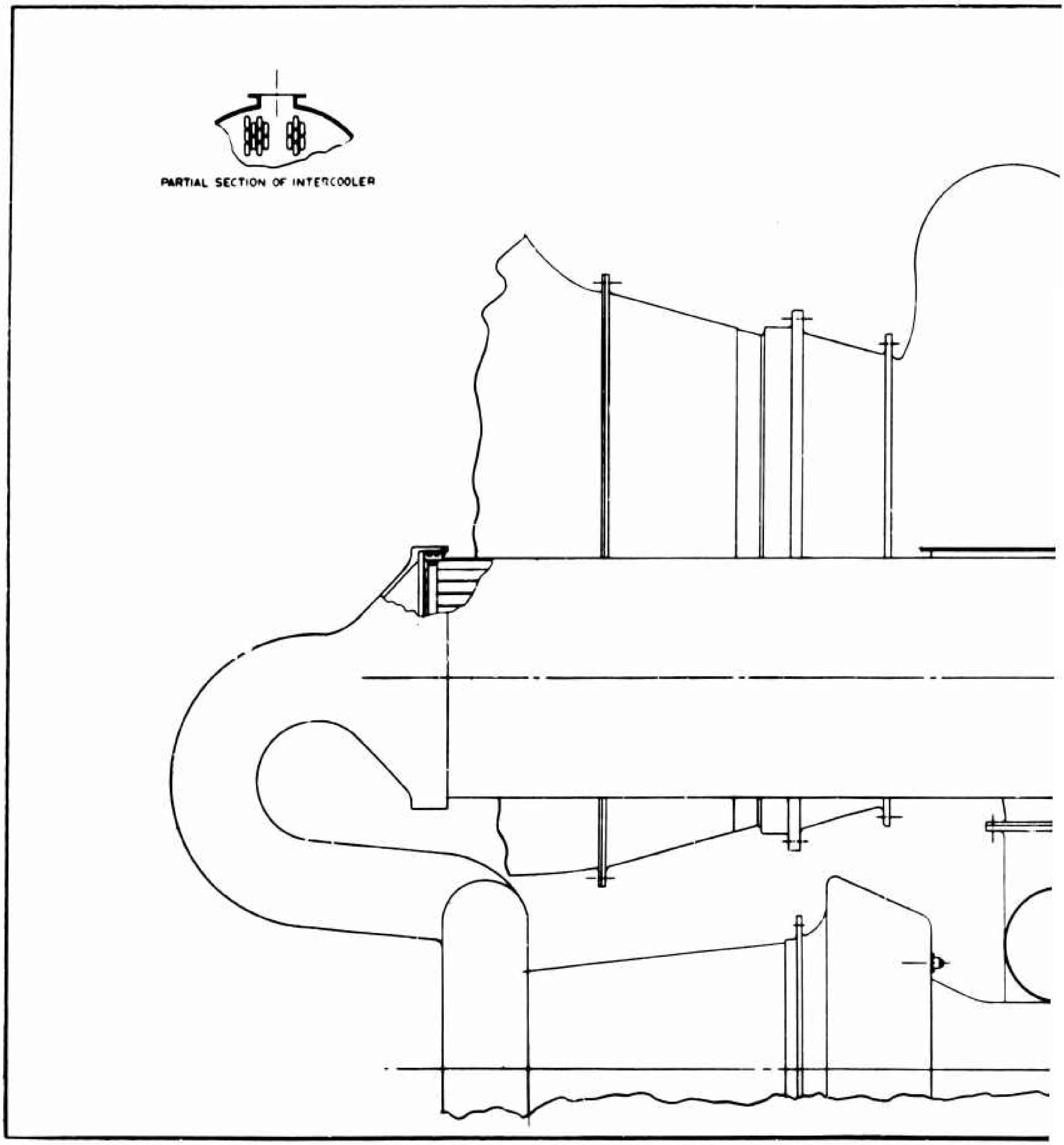
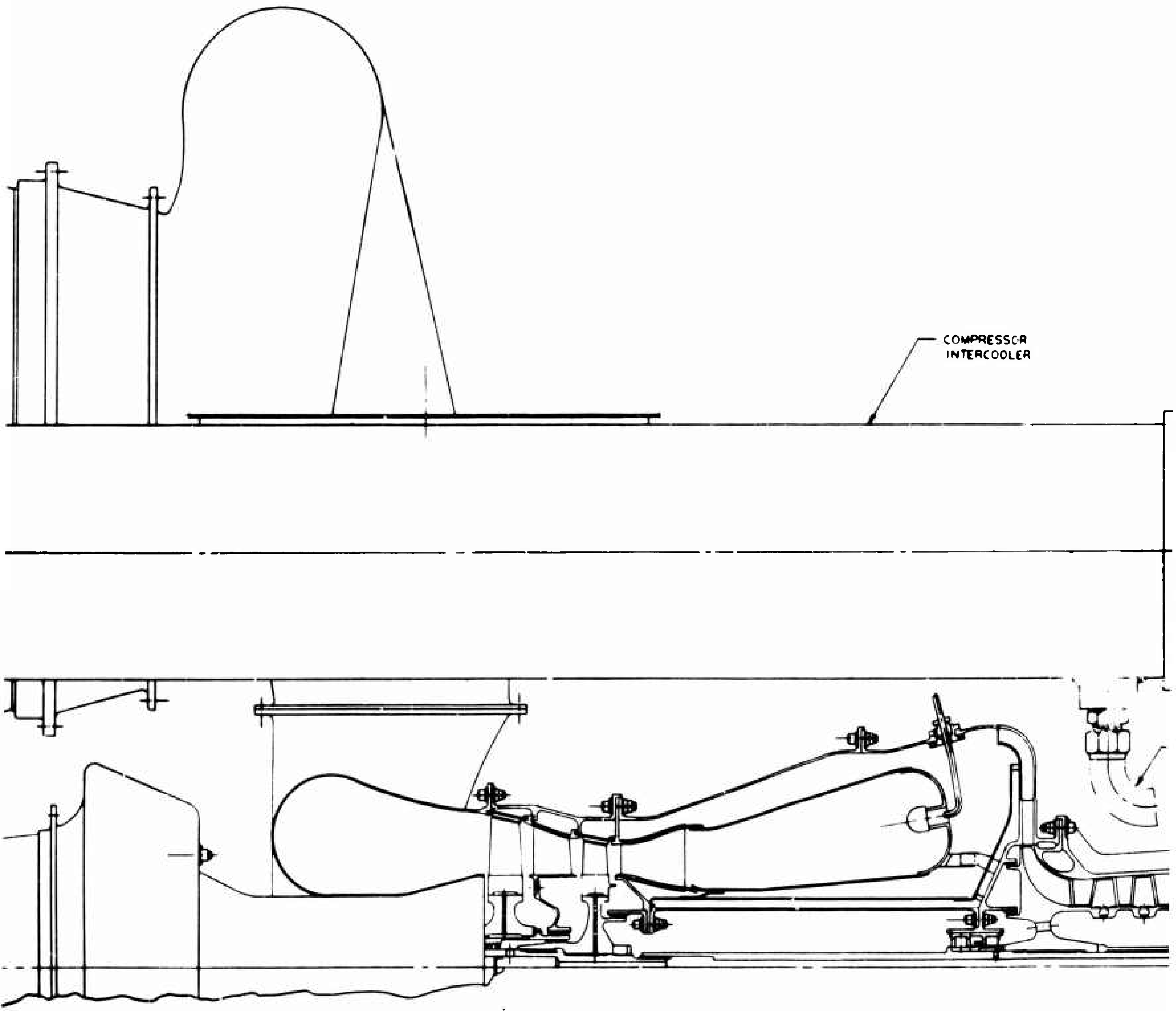


Figure 54. Typical non-regenerative engine with compressor intercooler.



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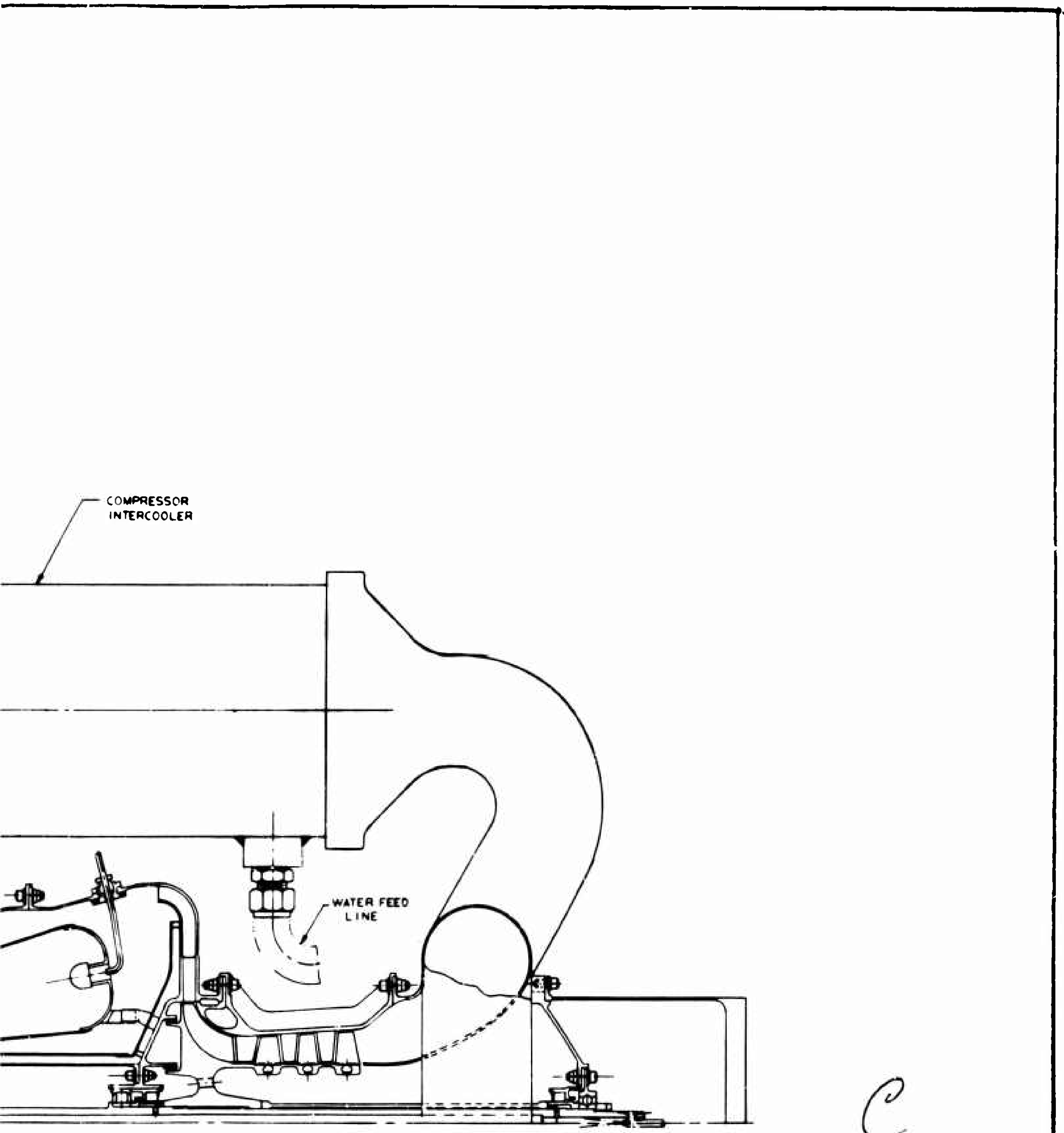

COMPRESSOR
INTERCOOLER
WATER FEED
LINE
C

VARIABLE-AREA POWER TURBINE DIAPHRAGMS

The variable-area nozzle shown on Figure 18 was based on an existing design, the hardware for which has been manufactured.

The individual partitions consist of an airfoil with integral spindles at inner and outer ends. The nozzle area is varied by rotating the airfoils about the spindles. This movement is effected by hydraulic rams, through bellcrank levers rotating a unison ring around the outside casing. The ring, in turn, actuates the lever attached to the end of the vane spindle.

Leakage from the gas passage by way of the vane bearing holes in the casings is reduced to a minimum by the use of piston rings riding in grooves machined in the vane spindles. The inside and outside walls of the gas passage are spherical about the centerline of vane rotation and have a radius equal to the gas passage radius in the plane of this centerline.

The inner and outer airfoil edges are spherically machined to match. By this means, the radial gaps between airfoil and casings are uniform for all positions of the vanes and leakage past the nozzle is minimized.

INTERBURNER

Mechanical designs which satisfied the aerodynamic requirement of the interburner could not be feasibly incorporated into the basic engines. This fact, coupled with the low levels of augmentation, led to a decision to drop the interburner from consideration as an augmentation system, and no mechanical designs showing the system were completed.

POST-TURBINE REGENERATOR BYPASS SYSTEM

Figure 55 shows the method of bypassing the heat exchanger by deforming the matrix. In the regenerating position, the matrix crosses the passage between two partitions for the full radial depth of the passage. Bypass flow area is produced by forcing the outermost edge of the matrix into a position parallel to one of the partitions. The resulting deformed shape of the flexible matrix opens a segment of the passage to bypass flow, as indicated in Figure 55.

A set of bellcranks, mounted on the rotating drum at the outer end of each passage, forces each matrix into the correct position. The bellcranks, in turn, are actuated through axial motion of a unison ring mounted within the stationary housing.

This method of bypassing thus eliminates the need for additional ducts for this purpose and provides bypassing of both hot and cold flows.

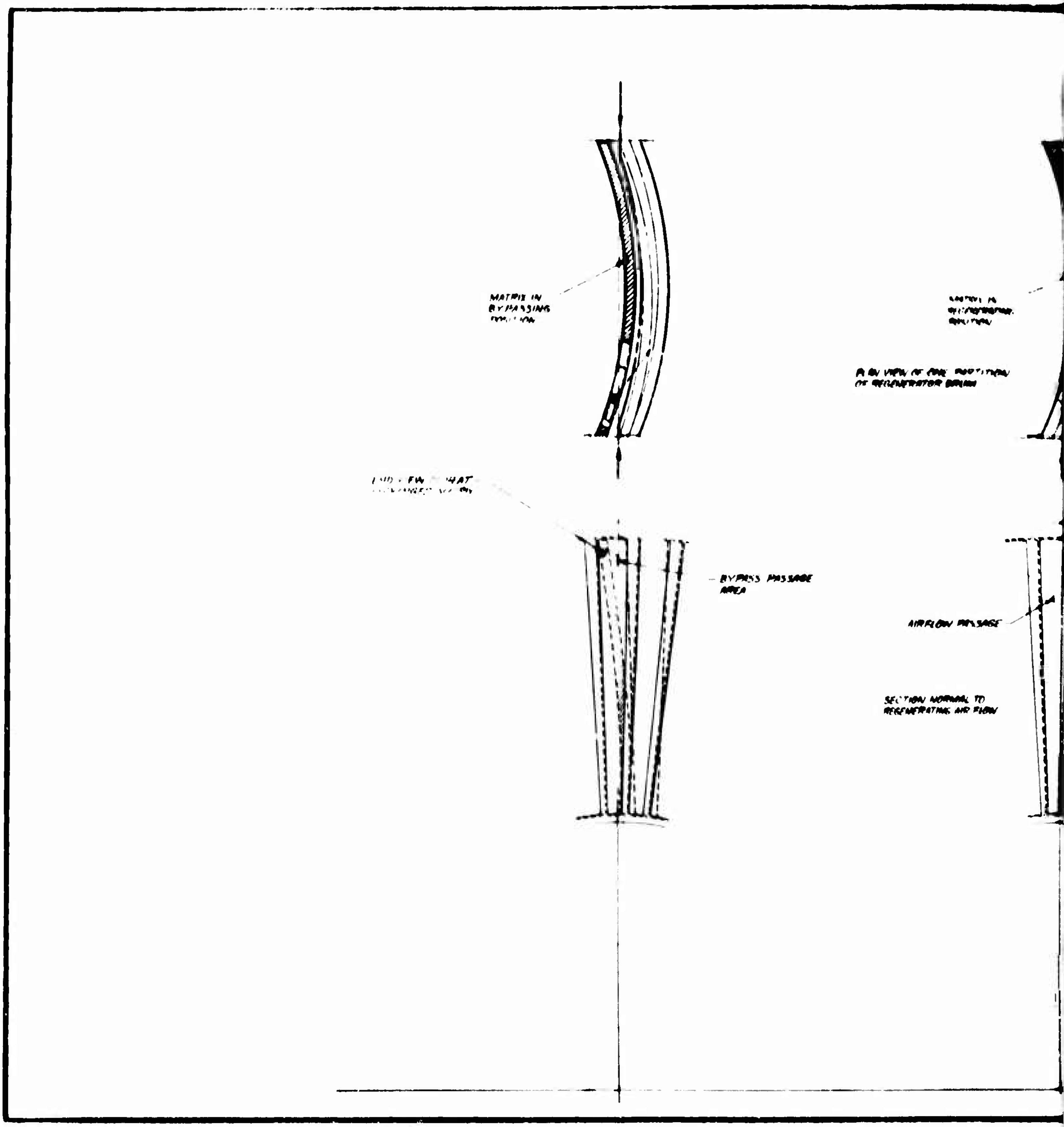
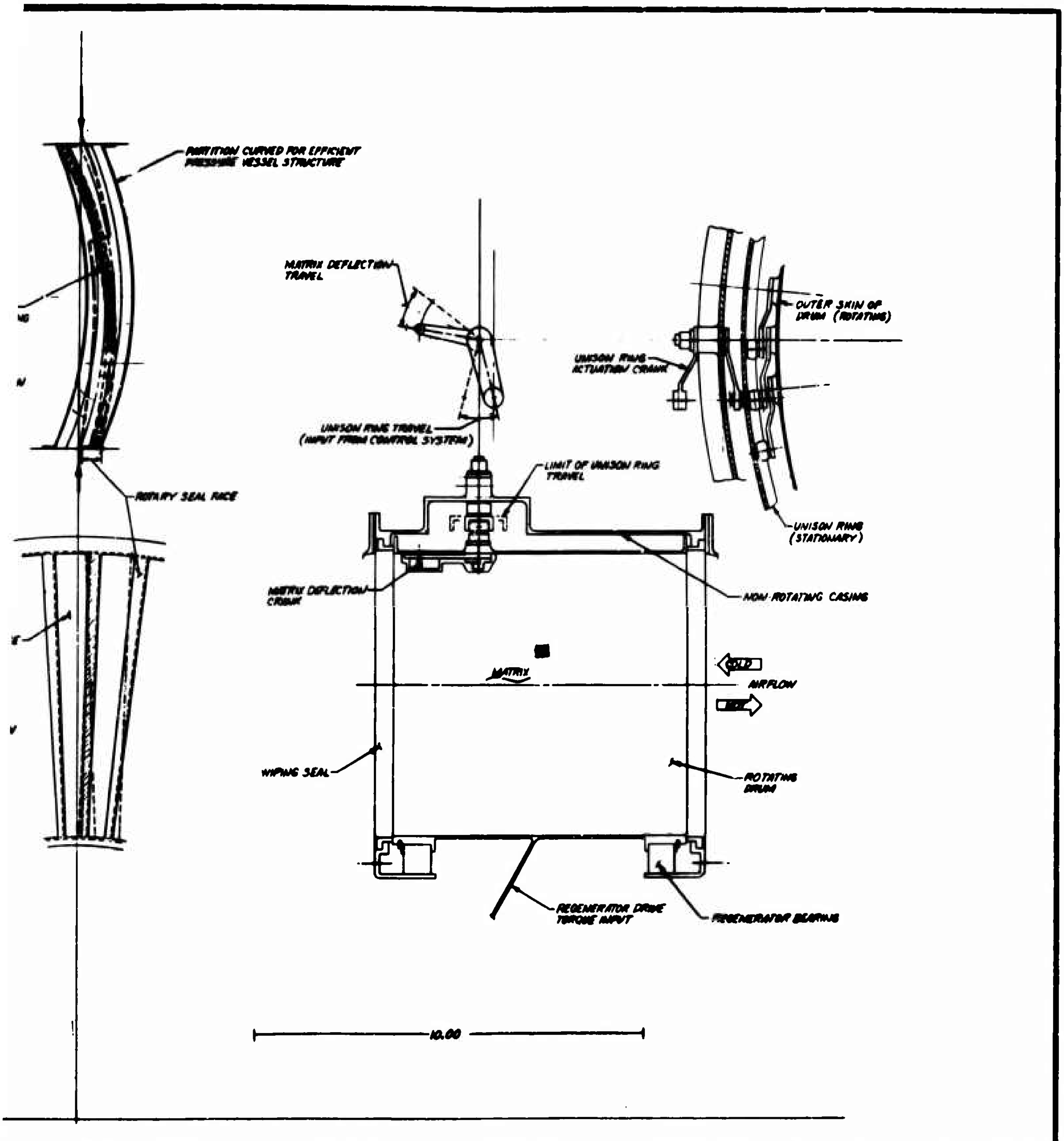


Figure 55. Details of post-turbine regenerator matrix.


PARTITION CURVED FOR EFFICIENT PRESSURE VESSEL STRUCTURE
ROTARY SEAL FACE
MATRIX DEFLECTION TRAVEL
UNISON RING TRAVEL (INPUT FROM CONTROL SYSTEM)
LIMIT OF UNISON RING TRAVEL
OUTER SKIN OF DRUM (ROTATING)
UNISON RING ACTUATION CRANK
UNISON RING (STATIONARY)
MATRIX DEFLECTION CRANK
NON-ROTATING CASING
MATRIX
AIRFLOW
WIPING SEAL
ROTATING DRUM
REGENERATOR DRIVE TORQUE INPUT
REGENERATOR BEARING
10.00

B

VARIABLE-AREA GAS GENERATOR TURBINE

The variable-area gas generator turbine required for the emergency power augmentation systems is shown in Figure 56. The design contains the same design features and operates in the same manner as the variable area power turbine; in addition, it has hollow spindles to allow for ducting of the diaphragm cooling air to the nozzle partitions.

HOT GAS INJECTION SYSTEM

The power turbine hot gas injection system, shown schematically in Figure 57, consists of a fuel storage tank equipped with a quick-opening valve, a nitrogen pressurization system to pressurize the fuel tank, a decomposition chamber containing the catalyst, and nozzles to duct the hot decomposition products from the decomposition chamber to the turbine inlet. When the injection system is activated, the operation of the quick-opening valve and the tank pressurization system starts the flow of fuel to the decomposition chamber, where it decomposes spontaneously, generating hot gas for injection into the power turbine. One-way check valves in the nozzle system prevent flow of hot gases from the engine into the decomposition chamber.

CHEMICALLY FUELED AUXILIARY POWER TURBINE

The auxiliary power source selected as representative of possible systems of this type was a monopropellant-fueled power turbine using the decomposition products of hydrazine as a fuel. This sytem consists of a prepressurized fuel storage tank equipped with a quick-opening discharge valve, a decomposition chamber containing a catalyst, and nozzles to duct the decomposition products from the decomposition chamber to the auxiliary power turbine. Opening the discharge valve starts the flow of fuel to the decomposition chamber, where it decomposes spontaneously generating the hot gas supp[illegible] needed to drive the turbine. The aerodynamic design data and the total fuel requirements for this system, based on a 1000-horsepower output, are shown in Table XIV and Figure 58.

AUGMENTATION SIZE AND WEIGHT

The size and weight of any given augmentation system were found to be dependent on the type of system, the size of the engine to which it was applied, and the augmentation ratio needed to obtain the required power level. Numerical values of augmentation system size and weight were determined by:

1. Selecting one of the basic engines.

2. Determining the augmentation ratio required to obtain the desired power output from that engine.

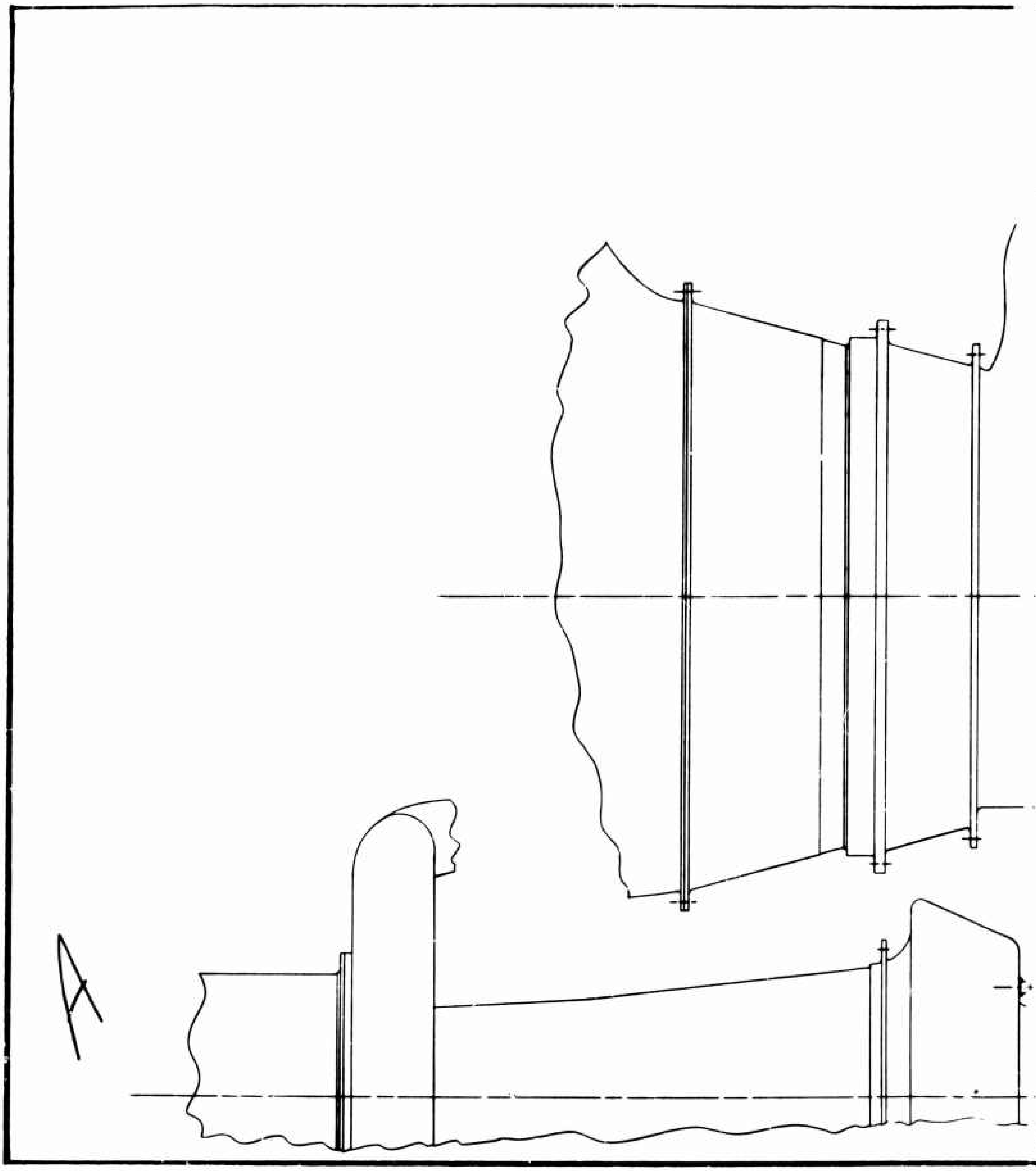
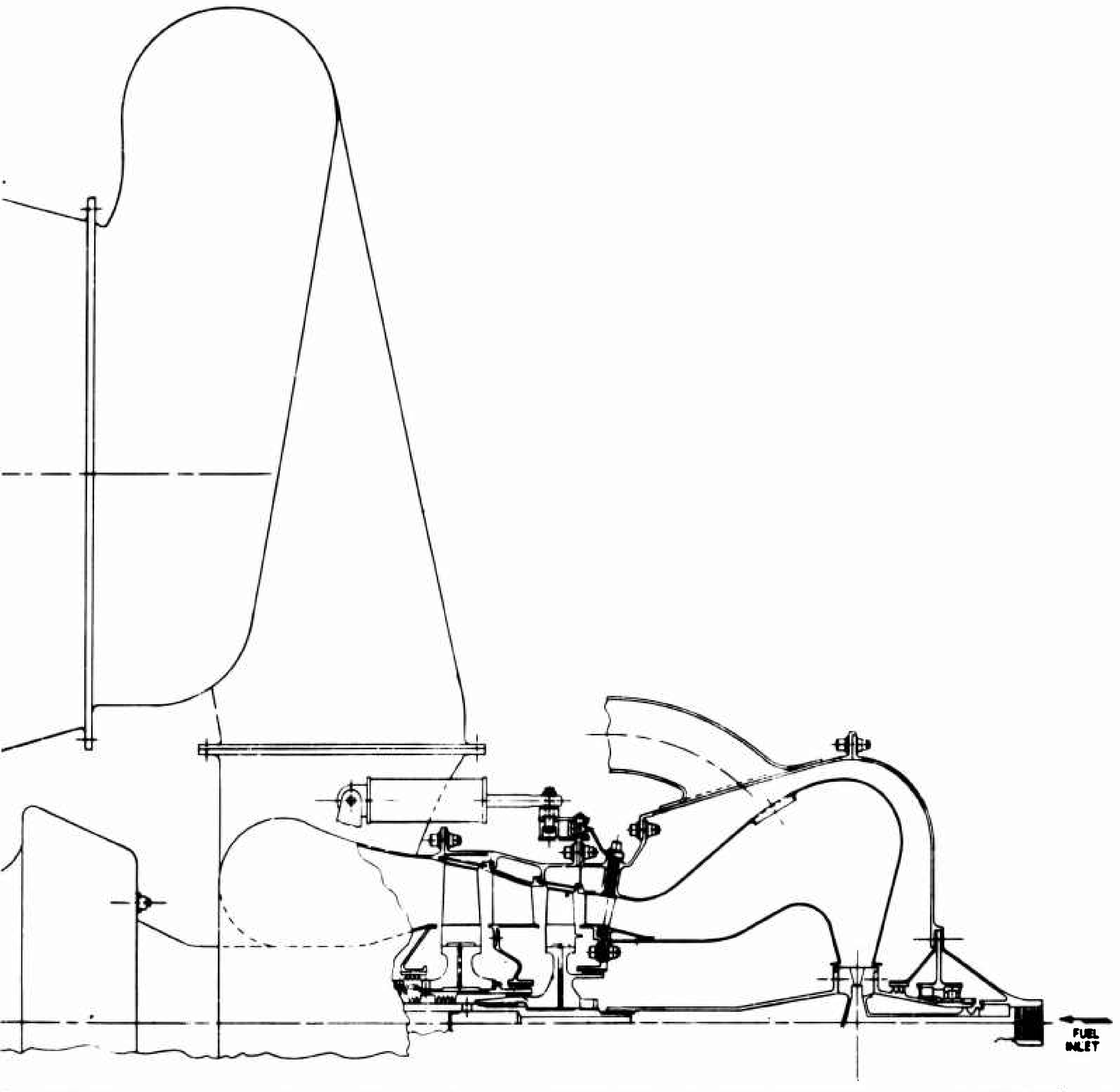


Figure 56. Typical non-regenerative engine with variable area gas generator turbine.



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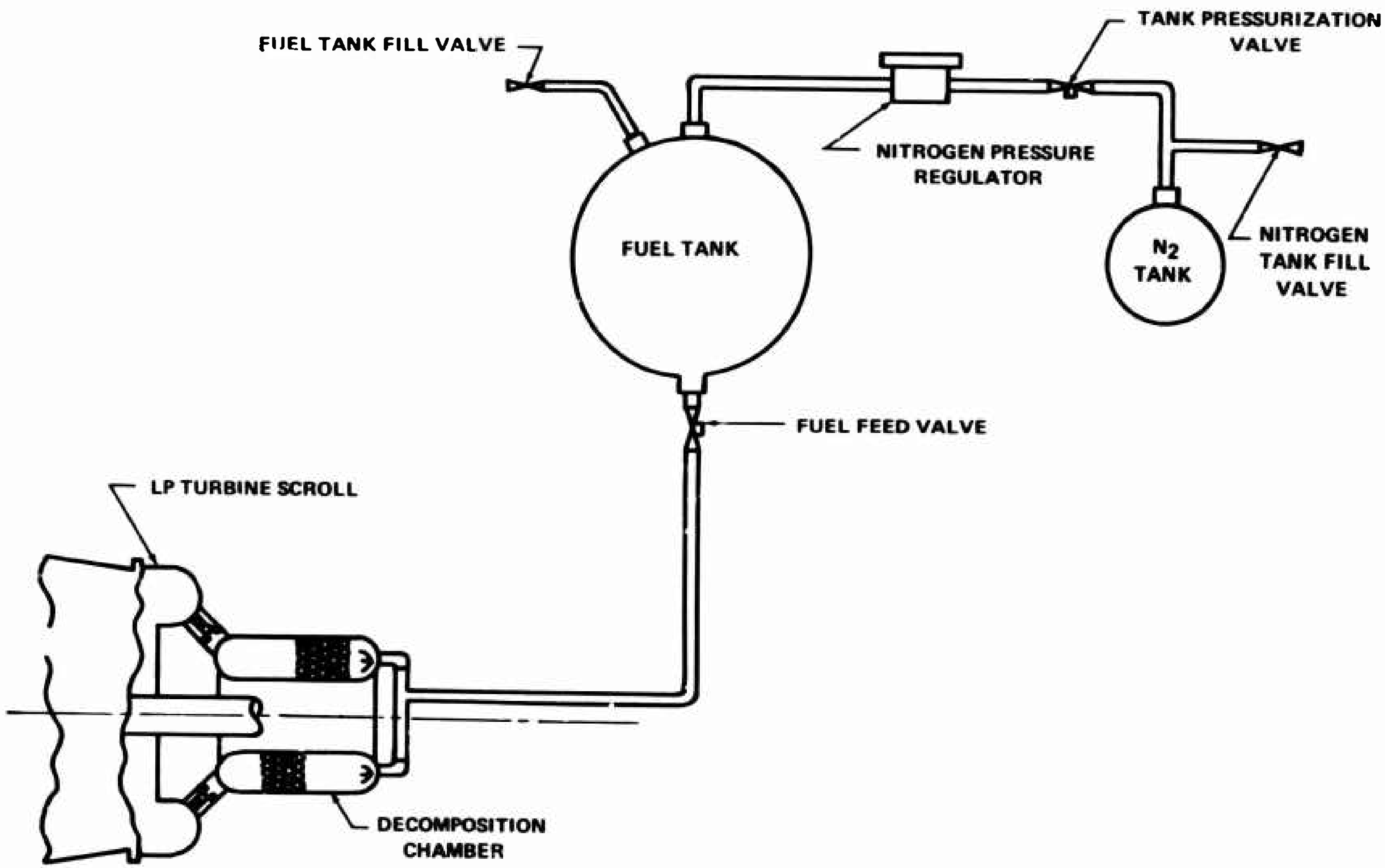


Figure 57. Power turbine hot gas injection system.

TABLE XIV

CHEMICALLY FUELED POWER TURBINE CHARACTERISTICS USING HYDRAZINE AS FUEL

	No. Stages		
	1	2	3
Weight Flow-lb/sec	4	3	2.5
Inlet Total Temp -°R	2160	2160	2160
Inlet Total Pressure - psia	37.5	50.3	63.9
Total-Static Effy - %	64	64	64
Δ h, Btu/lb	176.7	235.7	282.3
Tip Dia. - in.	12.8	10.28	9.2
N RPM	25000	25000	25000
Inlet Blade Height - in.	1.175	0.77	0.6
Exit Swirl - °	38*	33*	31*
Exit Mach No.	.44	.47	.46

* Exit guide vanes are assumed to remove swirl.

3. Selecting the particular augmentation system to be used to obtain the augmentation.

4. Entering the appropriate thermodynamic performance curve at the required augmentation ratio and reading off the value of the augmenting parameter required, or in cases where the desired augmentation ratio could not be reached, using the value of the augmenting parameter which gave maximum augmentation.

5. Calculating the weight and volume of any consumable materials required using the engine air flow rate, the value of augmenting parameter determined in 4 and the duration of operation of the augmentation system.

6. Calculating the weight of any tanks required to store these consumable materials and the weight of any lines and valves required to transport them to their point of use.

7. Calculating the weight of any other augmentation system components and the weight change associated with any required modifications to existing engine components.

8. Adding together the results of steps 5, 6, and 7 to obtain a total system weight.

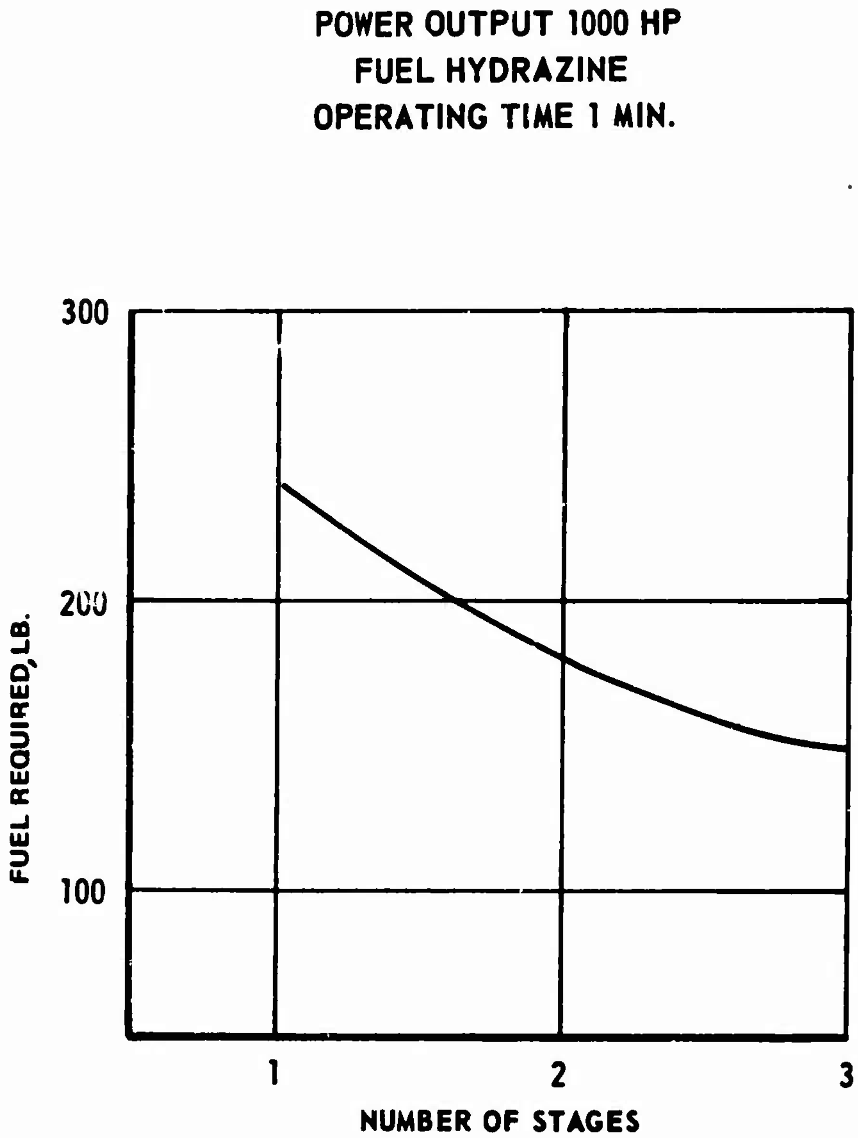


Figure 58. Chemically fueled power turbine fuel requirements.

The values obtained from this procedure for each hot day augmentation system basic engine combination are shown in Table XV; similar values for the emergency power system are shown in Table XVI.

In the case of the post-turbine regenerative engines, the engine is assumed to have been sized for takeoff at its design point without regenerator bypass, and each augmentation system was used in combination with bypassing the regenerator.
In the case of the inter-turbine regenerative engine, sizing of the engine for take-off with no bypassing negates the need for any other system for the hot day case since the resulting engine is approximately the same size as one sized at 6000 feet on a 95°F day with full bypassing.

Because of this fact, augmentation weights for the inter-turbine regenerative engines were calculated based on sizing of the engine, such that full bypass was required to deliver takeoff power at the design point.

TABLE XV

WEIGHTS OF 6000 FT, 95° F DAY AUGMENTATION SYSTEMS

Augmentation System	Engine Type and Sizing Point					
	Non-Regenerative		Post-Turbine Regenerative		Inter-Turbine Regenerative	
	SL Static 59°F	3000 Ft Static 78°F	SL Static 59°F	3000 Ft Static 78°F	SL Static 59° F	3000 Ft Static 78° F
Combined Compressor Water Injection and Overtemperature	80	40	68	-	81	41
Compressor Water Injection	114	56	94	31	116	57
Water-Alcohol	139	67	114	38	141	69
Turbine Overtemperature	22	14	22	13	22	13
Pre-Compressor Ammonia Injection	284	152	207	71	289	156
Compressor Intercooling	261	142	-	-	-	-
Combustor Water-Alcohol Injection	363	242	363	105	370	231
Tip-Turbine-Driven Zero-Stage Supercharger	445+	445+	445+	445+	445+	445+

TABLE XVI

WEIGHTS OF EMERGENCY ONE-ENGINE-OUT AUGMENTATION SYSTEMS

Augmentation System	Engine Type and Sizing Point								
	Non-Regenerative			Post-Turbine Regenerative			Inter-Turbine Regenerative		
	SL Static 59° F	3000 Ft Static 78° F	6000 Ft Static 95° F	SL Static 59° F	3000 Ft Static 78° F	6000 Ft Static 95° F	SL Static 59° F	3000 Ft Static 78° F	6000 Ft Static 95° F
Chemical Fuel Auxiliary	360	248	145	294	207	132	369	254	149
Chemical Auxiliary with Engine Overtemperature	265	135	44	208	116	69	278	148	45
Pre-Compressor Water Injection	-	-	39	-	-	-	-	-	40
Combustor Liquid Injection	-	-	170	-	-	-	-	-	213
Overtemperature and Pre-Compressor Ammonia Injection	-	-	173	-	144	104	-	-	176
Combination System No. 1	342	244	-	-	-	-	354	252	-
Combination System No. 2	288	188	-	274	-	-	298	195	-

DISCUSSION OF THE ADVANTAGES, DISADVANTAGES, AND LIMITATIONS OF THE AUGMENTATION SYSTEMS

ALTITUDE HOT DAY SYSTEMS

Each of the augmentation systems studied had good and bad features, in varying degrees, which were functions of the manner in which the system accomplished its augmentation and whether or not it was supplying hot day or emergency power. A brief discussion of these factors divided into categories of advantages, disadvantages, and limitations follows in this section.

Limitations Imposed by the Compressor Characteristics

One factor to be considered in evaluating the results of an augmentation study of this type is the performance characteristics of the compressors used. The engines shown have compressors with high tip speeds, high stage loadings, and assumed operating line characteristics as shown in Figures 20 through 23.

The influence of the compressor performance characteristics on augmentation potential shows up primarily in the manner in which corrected flow changes with corrected speed. In the high corrected speed operating region, which is of interest during augmented engine operation, this relationship can vary from less than 1 percent upward to a 3 percent change in flow for each percent change in speed. The maximum corrected flow obtainable also varies from 105 to as high as 120 percent of design flow. The characteristics of compressors with high tip speed and loadings fall generally in the low end of these ranges, while compressors with characteristics which fall into the high end of the range generally are lightly loaded and have lower flow per unit frontal area.

Of the augmentation methods studied, the only ones that do not involve some changes in compressor corrected speed and depend, to some extent, on flow increases for augmentation are interburning and overtemperature at constant speed. This consideration and the fact that the power output changes directly with changes in engine flow show that the results given are highly dependent on the characteristics assumed. As an example, the engine flow increase in the ammonia injection study, going from the zero ammonia air ratio point at 96.8 percent corrected speed to the 105 percent corrected speed point, gave a corrected flow increase of 10 percent. Over the same speed range for a typical engine having a high rate of change of corrected flow with corrected speed, the flow change would have been 26 percent, giving an augmentation ratio of 50 percent rather than the 31.5 percent actually obtained.

Other compressor characteristics which are also dependent on the compressor design and which influence the augmentation potential in the same general manner, although to a lesser extent, are the compressor corrected speed limit and the rate of change of compressor efficiency with change in corrected speed. The results shown in this report, then, are highly dependent on the assumed compressor characteristics and should be altered accordingly if they are to be applied to engines which have characteristics which differ considerably from those shown.

Compressor Inlet Water or Water-Alchol Injection

Advantages:

The system can supply the power augmentation required.

The system weight is one of the lowest of those studied.

The direct effects on unaugmented engine operation are negligible.

Development risk would be low.

The system would be simple and easy to maintain.

There are no hazards involved in handling the liquid.

Disadvantages:

Uneven water spary pattern can cause inlet temperature distortion problems.

The system is less suitable for application to the low-pressure-ratio post-turbine regenerative engine than to the non-regenerative engine.

The compressor must be designed with sufficient blade clearance to prevent blade tip rub when the water evaporation cools and shrinks the compressor casing. Any excessive clearance required could slightly reduce the compressor efficiency during unaugmented operation.

The logistics problems of providing relatively clean water or water-alcohol are in addition to normal supply requirements. If distilled water is not available, it may become necessary to water-wash the engine to remove deposits left when the water that is used evaporates.

Erosion of front stage compressor blades is possible.

Control modifications are required if the augmentation ratios shown in Figure 24 are to be achieved.

Limitations:

Limitations on the augmentation are a function primarily of the compressor's ability to evaporate the liquid injected. The highest liquid/air ratios are suitable for high-pressure-ratio compressors, where higher exit temperature and longer residence time result in high evaporation rates. As an example of the magnitudes of the water/air ratios which can be accommodated in the compressor, tests of the 14 stage 12:1-pressure-ratio T64 showed that it was able to evaporate 3 percent water injected into the compressor; while similar tests on the 10-stage 8:1-pressure-ratio T58 indicated that all the water was not evaporated when water/air ratios in excess of 1.5 percent were used.

Of the engines studied, the 17-to-1-pressure-ratio non-regenerative engine should have no problem evaporating the water required to restore power to its sea level static standard day rating. The low-pressure-ratio post-turbine regenerative engine, however, will undoubtedly have difficulty reaching this goal, even with the regenerator bypassed.

Turbine Inlet Overtemperature

To satisfy the requirement that hot day augmentation methods should not reduce the engine operating life, overtemperature was accomplished by using a heat exchanger to cool the fraction of compressor discharge air used for cooling hot parts. The heat exchanger used the aircraft fuel as a heat sink, with a resulting 200^{o}F drop in the cooling air temperature.

Advantages:

Lowest weight increase of any system.

No additional logistics problems.

No penalty in unaugmented engine operation.

Simple, maintainable, and reliable system components.

System adaptable to emergency power augmentation.

Disadvantages:

The maximum augmentation ratio is only 92 to 94 percent of the value required for engine sized at sea level static.

The method is not a proven technique, and whether it would have no effect on engine life would require tests to prove its merit.

Limitations:

The limits on this system are imposed by the turbine materials and the heat-sink capability of the fuel supply. The cooler design is based on an allowable temperature rise in the fuel of 25°F, starting from a possible tank temperature of 150°F; under these conditions, the total fuel supply is circulated once through the cooler during the 5-minute augmentation period. The pump for the system is a high-volume, low-pressure centrifugal design, and the cooler is a conventional shell and tube design. The total weight for the system is 22 pounds.

Combination of Compressor Inlet Water Injection and Turbine Inlet Over-temperature

The combination of compressor inlet water injection and turbine inlet overtemperature has some additional advantages over either system and adds no new disadvantages. The additional advantages are:

The total system weight is less than the weight for water injection alone.

The system will supply the required augmentation without exceeding limits in any of the engine types studied.

The use of water injection lowers the compressor discharge temperature and eliminates the need for the auxiliary cooler used with the pure overtemperature system.

The maximum temperature levels required are lower.

Pre-Compressor Ammonia Injection Combined With a Variable-Area Power Turbine

Advantages:

The system has the ability to supply the augmented power required when combined with a variable-area turbine for use in the non-regenerative or inter-turbine regenerative engine and individually for the post-turbine regenerative engine.

The direct effect on unaugmented engine operation is negligible.

The system is simple in operation and maintenance.

The system is compatible for use in engine emergencies.

The system's augmentation capabilities are less sensitive to changes in ambient temperature and humidity than the water injection system.

The high vapor pressure allows the ammonia to evaporate before it enters the compressor, and since the compressor pressure ratio is not a factor in the evaporization process, ammonia injection is suited to each engine type.

Entrance of ammonia into the compressor as a vapor eliminates problems with deposits, compressor case shrinkage, and blade erosion.

Disadvantages:

The total weight of the system is more than twice as great as that of a water injection system.

Supplying ammonia in the field would add to the logistics problem.

The ammonia would tend to attack rubber seals and gasket materials which it comes in contact with as part of compressor bleed air.

Ammonia is toxic and could present some handling problems.

Although none of the ammonia injection test results surveyed indicated any incidence of explosion, ammonia/air mixtures at elevated temperature and pressures, as would exist at the rear stages of the compressor, are known to have explosive potential. Since the ammonia/air ratios required for augmentation are below the normal combustion limits of 9 percent, this may not be a problem.

Non-uniform distribution of the ammonia in the inlet annulus could create compressor aerodynamic problems due to temperature distortion.

The high vapor pressure and the rapid rate at which it changes require a secondary pressurization system to control flow rate, which adds considerable weight to the system.

Limitations:

The limit on the amount of augmentation obtainable is imposed by engine overspeed and stall consideration rather than the ability to evaporate the ammonia. It was this fact which made the use of a variable-area power turbine mandatory for the non-regenerative engine.

The amount of data presently available, which is applicable to a direct assessment of the possible material problems associated with using ammonia, is limited. Accurate evaluation of any detrimental effects would have to be determined from test data, and a long development program might be required to prove the acceptability of an ammonia injection system.

Compressor Intercooling

Advantages:

Separation of the cooling medium from the engine air stream eliminates potential problems with deposits and compressor case shrinkage and blade erosion which exist in direct water injection systems.

The use of plain water rather than a mixture of water-alcohol is also preferable because of the higher latent heat of plain water, and this lessens the logistics supply problem.

The system is less sensitive than water injection to changes in ambient conditions.

The system components are simple, reliable, and maintainable.

Disadvantages:

Application of cooling midway through the compression gives a less efficient use of the coolant and requires more of it.

The intercooler will not produce the required augmentation even with the high-pressure-ratio engine, and it is not applicable to low-pressure-ratio engines.

Use of an intercooler introduces an additional pressure loss in the system which will reduce unaugmented performance unless extra components are included to allow the intercooler to be bypassed.

The total system weight without the bypass feature is two and one-quarter times the weight required for a water injection system.

The step change in temperature may result in mismatch problems between the two compressors.

Limitations:

The only practical system for intercooling the compressor flow from a total weight standpoint is one in which the coolant undergoes a phase change to take advantage of its latent heat. The temperature at which the coolant boils then sets a lower limit on the temperature to which the air can be cooled and determines the level of augmentation that can be attained.

Combustor Liquid Injection

Advantages:

Combustor liquid injection is a simple system of proven design and operation which imposes no penalty on unaugmented engine operation (Reference 3).

It is applicable to each of the three types of engines studied and will supply all of the augmentation required for four of the six basic engines which required hot day augmentation.

Disadvantages:

The use made of fluid injection at the combustor is relatively inefficient; as a result, the system is heavy compared to systems using compressor inlet injection.

The augmented power output is not as high as that required for the non-regenerative engine or the inter-turbine regenerative engine sized at sea level static standard day conditions.

A high-pressure high-flow pump or a high-pressure gas storage system is required to pump the liquid into the combustor.

Supplying the liquids creates logistics problems which are additional to the logistics of supplying an unaugmented engine.

Two factors contribute to the augmentation limit: compressor stall and the ability of the combustor to evaporate the mass injected. Injection of mass into the combustor has the effect of reducing the available turbine area through which the compressor discharge flow must pass. At constant speed in the high corrected speed range, the compressor flow is nearly constant; and for the flow to pass through the available turbine area, the compressor discharge pressure must increase. In the engine studies, the unaugmented engine stall margin was set at 20 percent to allow for the adverse Reynolds number effects when flying at altitude conditions. This extra stall margin is available at takeoff and was used up during augmented operation until only 7 percent remained at the limiting liquid-to-air ratio. Further reduction of the stall margin would not be advisable.

The ability of the combustor to evaporate the mass injected is a function of the velocity of flow through the combustor, the combustor length, and the operating temperature. Extrapolation of data from previous tests on the J47 and from tests where water entered the combustor of the T58 after compressor injection led to a prediction that up to 11 percent water could be injected in the combustor before liquid droplets started slugging into the turbine. The use of water-alcohol in this application is preferred over water because it minimizes the changes required in the normal fuel flow schedule by providing the heat of combustion required to bring about its own evaporation.

Interburning

Advantages:

> The system creates no additional logistics problems because it burns the same fuel as the main combustor.

Disadvantages:

> Insufficient power augmentation.
>
> High, dry pressure losses which adversely affect the engine performance during unaugmented operation.
>
> Volume requirements which make the interburner disproportinately large relative to the other engine components and increase the engine performance losses.

Limitations:

> The amount of augmentation which the interburner is capable of supplying is a direct function of the temperature rise, that can be safely achieved in the interburner. This safe temperature rise level is determined by the gas generator turbine discharge temperature and the limiting value of inlet temperature which the power turbine can stand. For the engines studied, the power turbines are an uncooled design and the temperature limit is 1850°F. At the 2200°F gas generator turbine inlet temperatures used, the gas generator turbine discharge temperatures were:
>
> Non-Regenerative Engine 1480°F

Inter-Turbine Regenerative Engine 1560°F

Post-Turbine Regenerative Engine 1675°F

This limited the allowable interburner temperature rise to 370°, 290°, and 175°, respectively, for each of the engine types; at these low temperature rise levels, the augmentation obtained was inadequate.

Attempts to increase the allowable temperature rise and augmentation, using a cooled power turbine, showed that the losses associated with supplying cooling air tended to offset the gains from higher power turbine inlet temperatures and the overall performance was not significantly improved.

The problems of high, dry pressure loss and combustor volume are interrelated and ultimately must be compromised to make both values reasonable. In this study, the high limit on dry-pressure loss was initially set at 5 percent, and a design was evolved which would meet this requirement. The design was 15 inches long and 12 inches in diameter and did not fit well into any engine configuration. Two factors are primarily responsible for this large size: (1) At entry to the burner, the gases are of low density and require large areas to obtain the inlet Mach numbers required; (2) Since the burner is feeding into a power turbine, it must have a good pattern factor and it requires excessive length to achieve good temperature mixing with a low, dry pressure loss. A second design with 7 percent loss reduced the burner length to 10 inches, but even the smaller size could not be incorporated in a reasonable manner into the engine, thus reinforcing the reasons for rejecting use of an interburner.

The combination of an intercooler with the interburner improves the total system augmenting ability at the expense of system weight, logistics problems, and increases in the engine bulk and pressure loss. The combined system still falls short in performance and, with increases in its disadvantages, was not considered to be a practical augmentation system.

Zero Stage Supercharging Using a Tip Turbine Drive

Disadvantages:

The level of augmentation was less than one-half the amount required.

The total system weight was the highest of any of the methods evaluated.

A mechanically complex system is required to allow bypassing of the supercharger when it is not needed.

Limitations:

The failure to achieve higher augmentation can be attributed to the supercharger's partially self-defeating feature; namely, the fact that the increase in temperature of the air as it is compressed in the supercharger decreases the corrected speed and flow of the main compressor, partially offsetting the flow increase which comes from increased air density at the compressor inlet. The actual augmentation achieved was only 12 to 18 percent, depending on the type of engine to which the system was applied.

The high system weight is attributable to the design limitations imposed on the turbine by the speed, size, and work requirements of the supercharger. These requirements resulted in a single-stage turbine with partial arc admission which was low in static efficiency and low in utilization of the available temperature, resulting in relatively high flow requirements for the stored gas generating materials.

Because of the weight requirements of the consumable stores and tankage, and the low level of augmentation achieved, work on the system was discontinued before mechanical designs were completed.

The combination of ammonia injection before it enters the supercharger resulted in achievement of the desired power level, but the weight increased an additional 122 pounds.

EMERGENCY POWER AUGMENTATION SYSTEMS

Simple Augmentation System

Factors affecting the requirements of an augmentation system for emergency power generation, as compared to the requirements for hot day power generation as defined in this study, were the amount of augmentation required, the time duration over which it must operate, and the ambient conditions existing when the augmentation is employed. The general consequences of these differences in the advantages and disadvantages of an augmentation system, as applied to one case or the other, are:

Advantages:

> Systems where consumable stores are a major portion of the system weight improve in relative desirability compared to the systems where hardware is the major weight factor, due to the shorter duration of use.
>
> The higher mechanical and thermal loads associated with augmentation are less restrictive due to the shorter duration of their application.

Disadvantages:

> The augmentation ratio obtainable before reaching an engine operating limit for an engine operating at standard temperature is lower than the augmentation ratio obtainable before reaching the same limit at hot day temperature. This fact, and the fact that a higher augmentation ratio is required for emergency power augmentation made the simple systems which were suitable for hot day augmentation unsuitable for emergency power augmentation except when combined with the engine sized for the 6000-foot 95°F condition.

Except for these changes, the advantages, disadvantages, and limitations of the hot day augmentation systems previously evaluated still apply when these systems are used individually or as parts of a multicomponent system for emergency power augmentation. Components which were applied only to emergency power augmentation were (1) a monopropellant fueled system for injection of hot gas into the power turbine and (2) a variable-area gas generator turbine. These have the advantages, disadvantages, and limitations which follow.

Hot Gas Injection System

Advantages:

The system is simple, is self-contained, and can be incorporated into the engine without introducing performance penalties during unaugmented operation.

The system can be initiated instantly, as required in emergency situations.

In combination with the other parts of the overall system, the required power can be obtained.

The system serves as an effective substitute for a variable-geometry power turbine which would otherwise be required.

The condition of the system can be monitored by external gauges, and maintenance requirements would be low.

Disadvantages:

The propellant consumption rate is relatively high, and the low pressure at which it must be injected to avoid upsetting the engine operation results in inefficient use of the available energy.

Although the handling of monopropellants, in general, presents no serious problems, care must be exercised to prevent contact of the monopropellant with combustible materials with which it can spontaneously ignite.

Supplying monopropellant in the field is an additional logistics problem.

Limitation:

The only real limitation on the use of the system is the ability of the power turbine to pass the added flow, which is dependent on the reaction of the engine to the other augmenting components used in the system.

The other new part incorporated into these augmenting systems is the cooled variable-geometry gas generator turbine. This, in itself, is not a method of augmenting power, but it is needed to make the engine capable of operating within its aerodynamic speed and stall limits with the required augmentation systems in operation.

Combination of Several Components in a Single System

Advantages:

The combined system will provide the augmentation required for any one of the basic engines.

Disadvantages:

Two or possibly three separate liquid storage systems, all of which must be initiated simultaneously, are required.

The amount of absolute power that the system supplies is dependent on the ambient condition during takeoff.

A complex control system is required to sequence and control the system operation in such a way as to prevent engine overspeed and/or stall.

In general, since failure of any one of the components to operate properly would cause the other components to move the engine operating point above the stall or corrected overspeed limit, the control would have to terminate all systems if one failed.

Examples of this would be:

Failure of the power turbine hot gas injection system, resulting in overspeed of the gas generator; or failure of the variable gas generator turbine operation, resulting in the compressor's being driven into stall.

The multiplicity of systems and their interdependence on each other give these combined systems a relatively low reliability compared to simple systems.

The use of the variable-geometry turbine will result in loss of maximum turbine efficiency. However, it is possible that the variable feature can be incorporated into the normal operation of the engine in a way which will improve part-power performance and offset the effect of lower efficiency. A study to optimize the feature, however, was not within the scope of this contract.

Of the multiple component systems, the second is preferred because elimination of the combustor injection in favor of additional pre-compressor injection reduces the system weight by 55 pounds and eliminates the third liquid system.

<u>Auxiliary Power Source</u>

Advantages:

The system is self-contained, and its use has no adverse effect on operation of the main engine systems during unaugmented operation.

The system can sit inactive but primed for long periods of time without loss of performance potential.

The system ignites spontaneously, and its reponse is fast enough to satisfy emergency requirements.

The power output is basically independent of ambient conditions and would improve with increasing altitude where normal engine power is decreasing.

The system is simple with only a few components and will have high reliability and low maintenance requirements.

The system is completely compatible with other augmentation systems which might be employed to provide hot day augmentation.

Disadvantages:

Supplying the monopropellant in the field adds to logistics problems.

There are potential hazards in handling the monopropellants, many of which are toxic and/or spontaneously combustible with many materials.

Limitations:

The limitations of an auxiliary system are those imposed on its power output and/or operating duration by the weight which it is allowed to attain.

DETERMINATION OF AUGMENTATION SYSTEM MERIT FACTORS

The final measure of value applied to the augmentation systems studied was a merit factor defined as the total installed weight of an engine plus any augmentation system used by the engine plus the total weight of fuel used for a typical helicopter mission. The merit factor equation and mission model used for this purpose are shown in Tables XVII and XVIII. This mission model was selected as representative of one mission on which the engines under study might be used.

TABLE XVII

MERIT FACTOR DEFINITION

The merit factor proposed for use in evaluating each of the engine augmentation combinations is:

$$M.F. = (W_E \times 1.25) + \sum_{i=1}^{6} (H_{Pi})\ (SFC_i) \times t_i$$

where

M.F. is the merit factor, pounds,

W_E is the engine plus augmentation system weight, pounds,

H_{Pi} is the horsepower required for the ith mission segment,

SFC_i is the SFC for the ith mission segment,

t_i is the time for the ith mission segment,

and the mission segments are as defined in Table XVIII.

TABLE XVIII

EVALUATION MISSION

Segment	Speed (kn)	Time (hr)	Engine Power Required as a percent of 4000 ft, 95° F Takeoff Power	Altitude Ft/Temp
Takeoff & Hover OGE	0	.085	100	4000 ft/95° F
Cruise	150	.50	55	Sea Level/59° F
Trip No. 1	150	.50	52	
Trip No. 2	170	.50	75	
Trip No. 3	150	.50	48	
Loiter plus Reserve	80	.915	20	Sea Level/59° F
		3 Hours		

The engine and augmentation system weights and the methods used to obtain them were described previously.

The fuel weight portion of the merit factor is the sum of the fuel required for each of the six segments of the vehicle mission, and it is a function of the vehicle power requirements and engine SFC. The power requirements used in this study are shown in Table XVIII as a percentage of the engine power required to fly the vehicle over each portion of the defined mission, when the engine has been sized at 4000 ft on a 95° F day. These values were taken from the curve of Figure 59 and reflect the effect of vehicle gross weight, vehicle speed, and ambient conditions on power required, as well as the effects of ambient conditions on engine power available. The engine SFC was obtained by running off-design performance calculations for each of the basic engines at each of the flight conditions listed in Table XVIII over a range of power levels from military to 20 percent of military power. Since the decision was made to compare engines of the same type at equal design power levels, the results obtained were scaled so that all engines of one type gave the same power at their design points where the reference used for scaling was the SL standard day design point. The results were then converted from SFC to fuel flow and plotted as fuel flow versus percent design SHP.

Changes in performance over the range of flight speeds were small enough so that a single curve was sufficient to represent each type of engine. These curves are shown on Figures 60 through 62. The total mission fuel requirements for any engine were then determined by substituting values from the fuel flow characteristics, the engine design values, and the mission definition into the summation portion of the merit factor equation, using the method shown in the example on page 136. The results obtained are shown in Tables XIX, XXII, and XXV and on Figure 66. Design point engine fuel flows are shown in Figures 63 through 65.

The merit factors for each engine-augmentation system combination were obtained by adding the weight of the fuel required to the weight of the installed engine with its augmentation system, using the procedures shown in the examples on pages 146 and 148 and the following definitions and assumptions:

> The merit factor for hot-day augmentation is based on one augmented engine and the mission fuel for that engine.
>
> Merit factors for emergency power are based on two engines with an augmentation system and the mission fuel for two engines.
>
> To give a better basis of comparison, all engines of one type deliver equal power when running at their ambient design point (example: non-regenerative = 1704 SHP); this is a variation of the 10 lb/sec criterion.

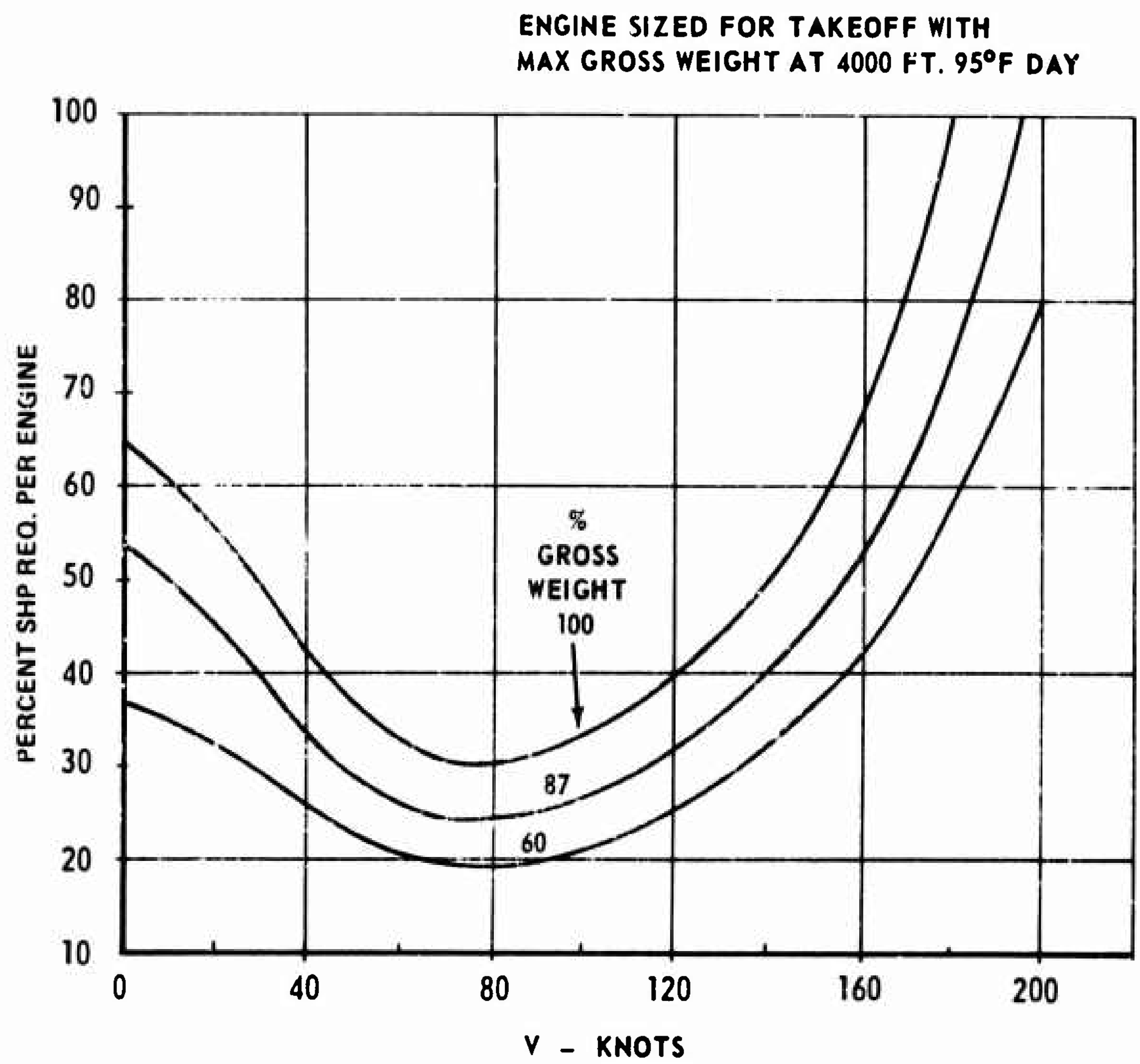


Figure 59. Helicopter engine power required,sea level,standard day.

Engines oversized to supply the maximum power required are used as a base point.

To determine installed system weight, the weight of the augmentation system is multiplied by the same factor as the base engine weight.

Where necessary, mission fuel requirements are adjusted to account for any loss in unaugmented performance caused by the addition of an augmentation system.

The results obtained for each engine-augmentation system combination are shown in Tables XIX through XXVIII and Figures 67 through 72, where data for the inter-turbine regenerative engine are based on engines sized to require full bypassing for takeoff at their design points.

Merit factors for the best combination of systems which are capable of providing hot-day altitude augmentation and emergency one-engine-out power are shown in Figures 73 through 79.

For comparison purposes, the best combination of an engine sized at the 6000 feet 95°F condition and an emergency power augmentation system is shown on each graph. Comparison of these systems with the lightest weight designs shows that the spread of total system weight among the combinations shown for the same type of engine is always less than 10 percent. Combinations not shown were in all cases heavier than the lightest weights shown. Among the different types of engines, the non-regenerative is, in all cases, the lightest weight design.

Discussion

Power Lapse Rate

The merit factors determined in this study were dependent, among other things, on the power lapse rate which occurred on each engine as the ambient condition changed from one extreme to the other. Considering the change in the conditions to occur as a two-step process of a change in altitude at constant temperature followed by a change in temperature at the new altitude, the effect on power lapse rate can be separated into that due to changes in ambient pressure and that due to changes in ambient temperature.

The altitude or ambient pressure effect is a simple relationship of a directly proportional change in engine power as ambient pressure changes with changes in altitude, since over the range of altitudes considered in this study, the effects of changes in component efficiencies due to changes in the pressure-dependent Reynolds number are not significant. The altitude portion of the lapse rate is then independent of any of the choices made in the selection of the engine cycle and components, but it directly affects the change in physical size required to maintain the engine power at the desired level.

On the other hand, the power lapse rate due to changes in ambient temperature is a complex function of such variables as compressor pressure ratio, turbine inlet temperature, engine control mode, and the rate of change of component efficiency levels and internal pressure losses as the engine operating point changes. Assuming a control mode of either constant turbine inlet or discharge temperatures, the most readily apparent effects of an increase in ambient temperature are a decrease in engine corrected speed and consequently corrected flow, and a decrease in engine specific power due to the increased compression work which results from higher ambient temperatures.

The effects which cycle pressure ratio and turbine inlet temperature have on specific power as ambient temperature changes from 59°F to 95° F can be calculated on a design point basis using constant airflow and efficiencies. This effect is shown in Figure 80 for non-regenerative engines. The effects which all of the variables have on the change in corrected speed and flow are dependent on each other and on specific engine characteristics, and they cannot be readily presented in parametric fashion.

For the specific engines with their assumed characteristics which were examined in this study, these effects resulted in changes in engine corrected speed of from 3.2 to 4.5 percent, with corresponding changes in corrected flow of from 5.5 to 8 percent. The resulting overall power lapse rate found in this study ranged from .67 to .71 as ambient conditions changed from sea level, 59°F to 6000 feet, 95°F.

The power lapse rates shown above are typical values for turboshaft engines operating in the range of ambient conditions considered in this study; however, if a set of assumptions had been used that resulted in lapse rates other than those shown above, some small changes would have resulted in the calculated merit factors. For example: for the engine-augmentation system combination selected as optimum (non-regenerative engine sized at 6000 feet, 95°F with water injection for emergency power), the power available at 6000 feet, 95°F was 67 percent of the power available at sea level, 59°F. If this value had been 1 percent lower, at 66.3 percent, then the weight of the engines and fuel required to perform a typical mission would have increased 30 pounds and the weight of the emergency power augmentation system would have decreased 5 pounds with a net increase of 25 pounds or 0.5 percent in merit factor. This rate of change is not of sufficient magnitude to change the conclusions.

SAMPLE CALCULATION OF MISSION FUEL REQUIREMENTS

NON-REGENERATIVE ENGINE,
DESIGN POINT 3000 FT, 78°F,
DESIGN POINT POWER 1704 SHP

1. The SL Standard day power SHP_A which is available when 1704 SHP is required for takeoff from 4000 ft on a 95°F day can be determined from the data of Table VI as follows:

Let Kp_1 be the ratio of power at 59°F to power at 95°F, and Kp be the ratio of power at SL 59°F to power at 4000 ft, 95°F; then

$$Kp_1 = \frac{2326}{1560} \times \delta_{6000}$$

$$Kp_1 = \frac{(2326)}{1560} \times .8013$$

$$Kp_1 = 1.1947$$

$$Kp = Kp_1 \div \delta_{4000}$$

$$Kp = 1.1947 \div .8636$$

$$Kp = 1.3834$$

The reference SL standard day power SHP_A then is

$$SHP_A = SHP \times Kp$$

$$= (1704) \times 1.3834$$

$$SHP_A = 2358 \text{ SHP}$$

2. The power required for each portion of the mission is then

$$SHP_R = (SHP_A) \times \frac{\% \, SHP_R}{100}$$

and using the percentage figures from Table XVIII, these values are

Mission Segment			Power
Take Off	1704 x 1	=	1704 at 4000 ft, 95°F
Cruise Out	2358 x .55	=	1297 at SL, 59°F
Trip No. 1	2358 x .52	=	1226 at SL, 59°F
Trip No. 2	2358 x .75	=	1767 at SL, 59°F
Trip No. 3	2358 x .48	=	1131 at SL, 59°F
Loiter & Reserve	2358 x .2	=	471 at SL, 59°F

3. The power available at 4000 ft, 95°F from an engine sized to deliver 1704 horsepower at 3000 feet can be calculated using the figures of Table VI as follows:

at 4000 ft, 95°F, the power is

$$SHP_{4000\ ft} = \left(\frac{1704}{SHP_R}\right) \times \left(SHP_{6000}\right)\left(\delta_{4000}/\delta_{6000}\right)$$

$$SHP_{4000\ ft} = \left(1704/_{1643}\right) \times (1354) \times .8636/_{.8013}$$

$$= 1513\ SHP$$

4. The fuel required for takeoff can be determined as follows:

SHP_R as percent design SHP

1513 = X% (1704)

1513 = 88.9 percent of 1704

Enter figure 63 at 88.9 percent

Obtain WF = 690 lb/hr

$WF_1 = WF \times t_1$

$WF_1 = 715 \times .085 = 58$ lb

5. Converting the horsepower required for the 2nd to the 6th portions of the mission to percent of design gives the results below:

SHP_R		Percent Design SHP		
1297	=	76.1	x	1704
1226	=	72.0	x	1704
1767	=	103.7	x	1704
1131	=	66.4	x	1704
471.3	=	27.7	x	1704

6. Using these percentage figures to enter Figure 60, and reading from the 3000 ft, 78°F design line, the mission fuel flows are:

Mission Segment	Percent Design SHP	W_f lb/hr	x	t hrs	=	W_f lb
2	76.1	634		.5		317
3	72.0	606		.5		303
4	103.7	780		.5		390
5	66.4	586		.5		293
6	27.7	397		.915		354

7. Summing the fuel flows for all mission segments,

$$W_{f_m} = \sum_{i=1}^{6} W_{f_i} = 58 + 317 + 303 + 390 + 293 + 354$$

$$W_{f_m} = 1715 \text{ lb}$$

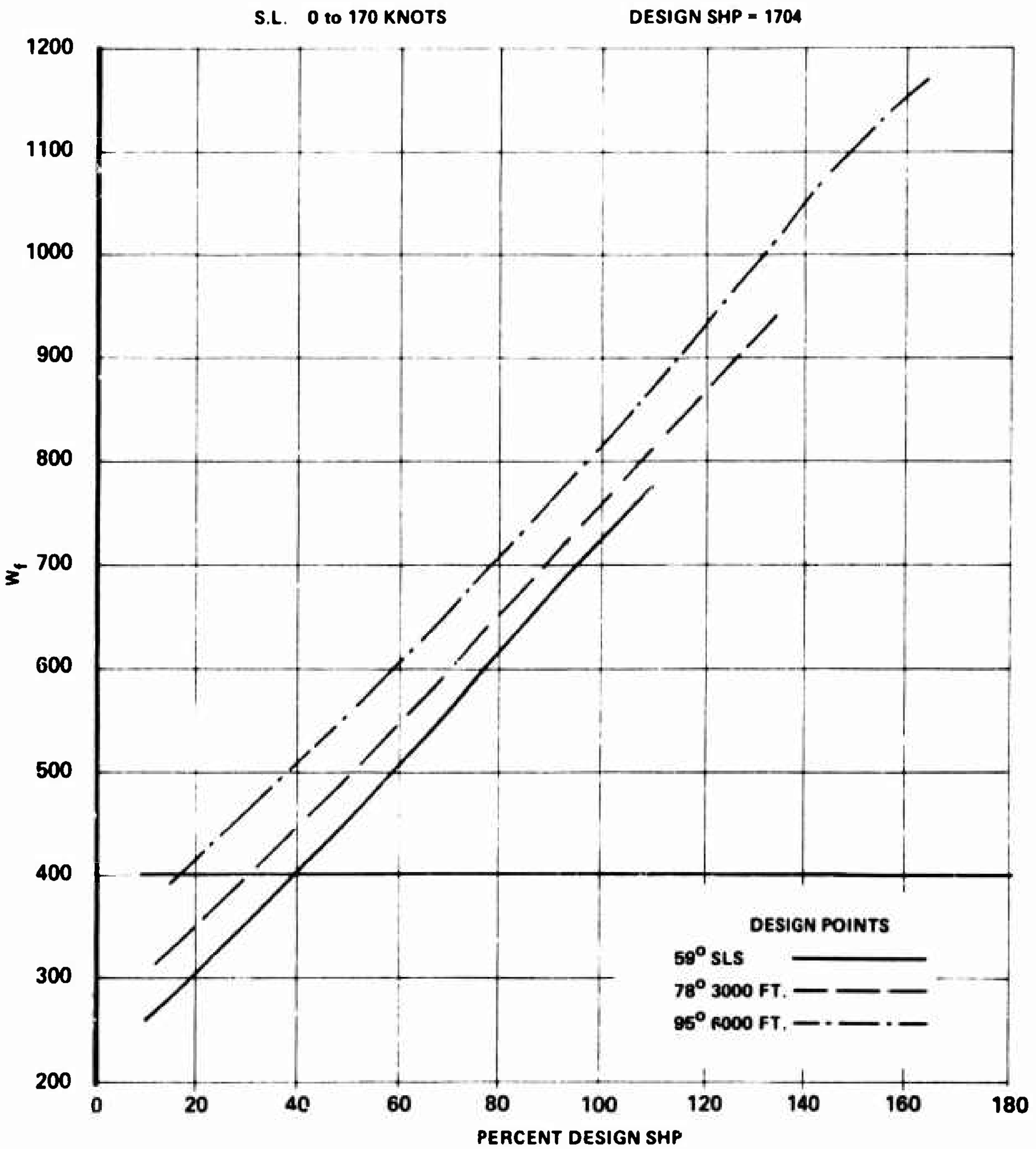


Figure 60. Non-regenerative engine fuel flow versus percent design shaft horsepower.

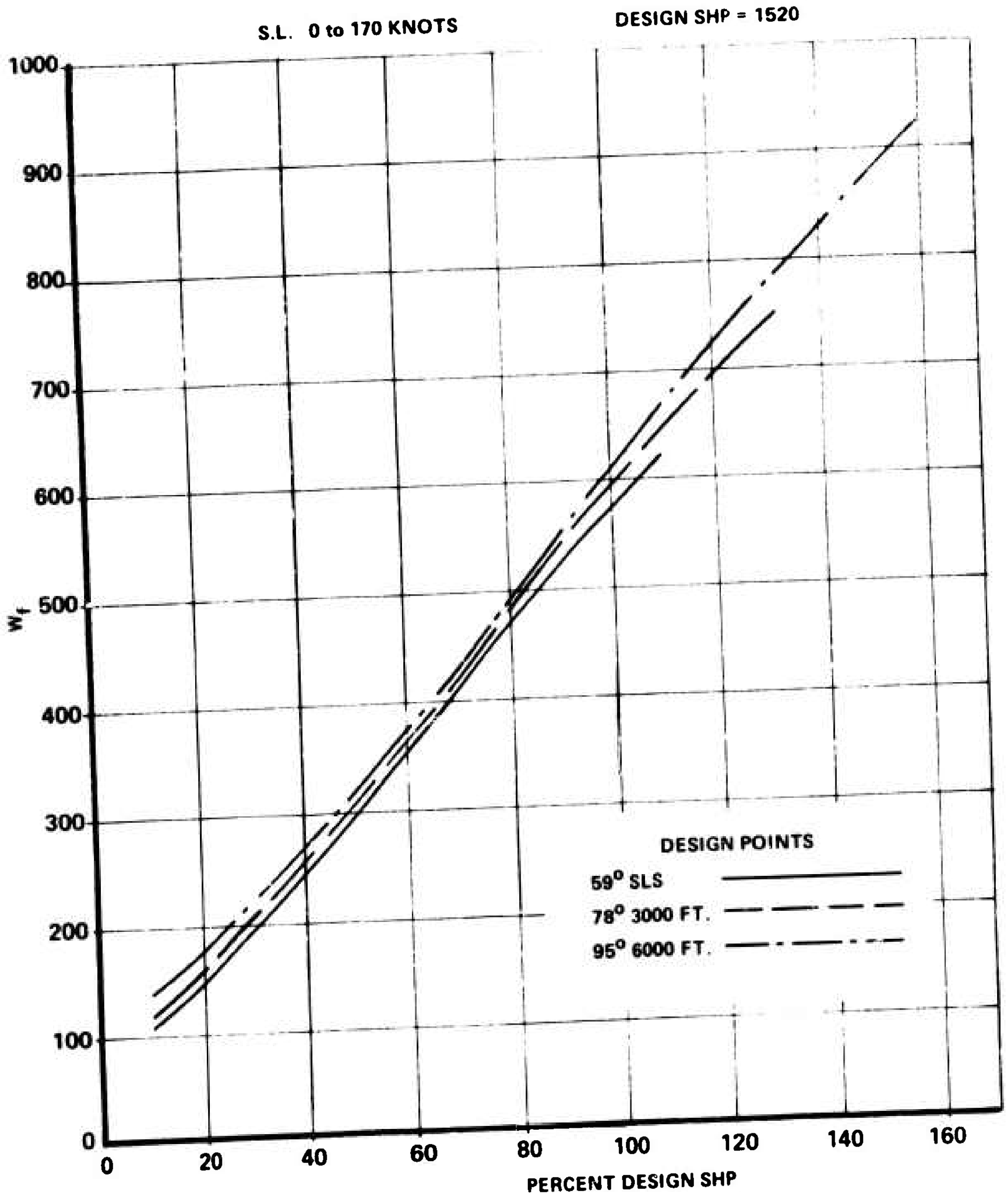


Figure 61. Post-turbine regenerative engine fuel flow versus percent design shaft horsepower.

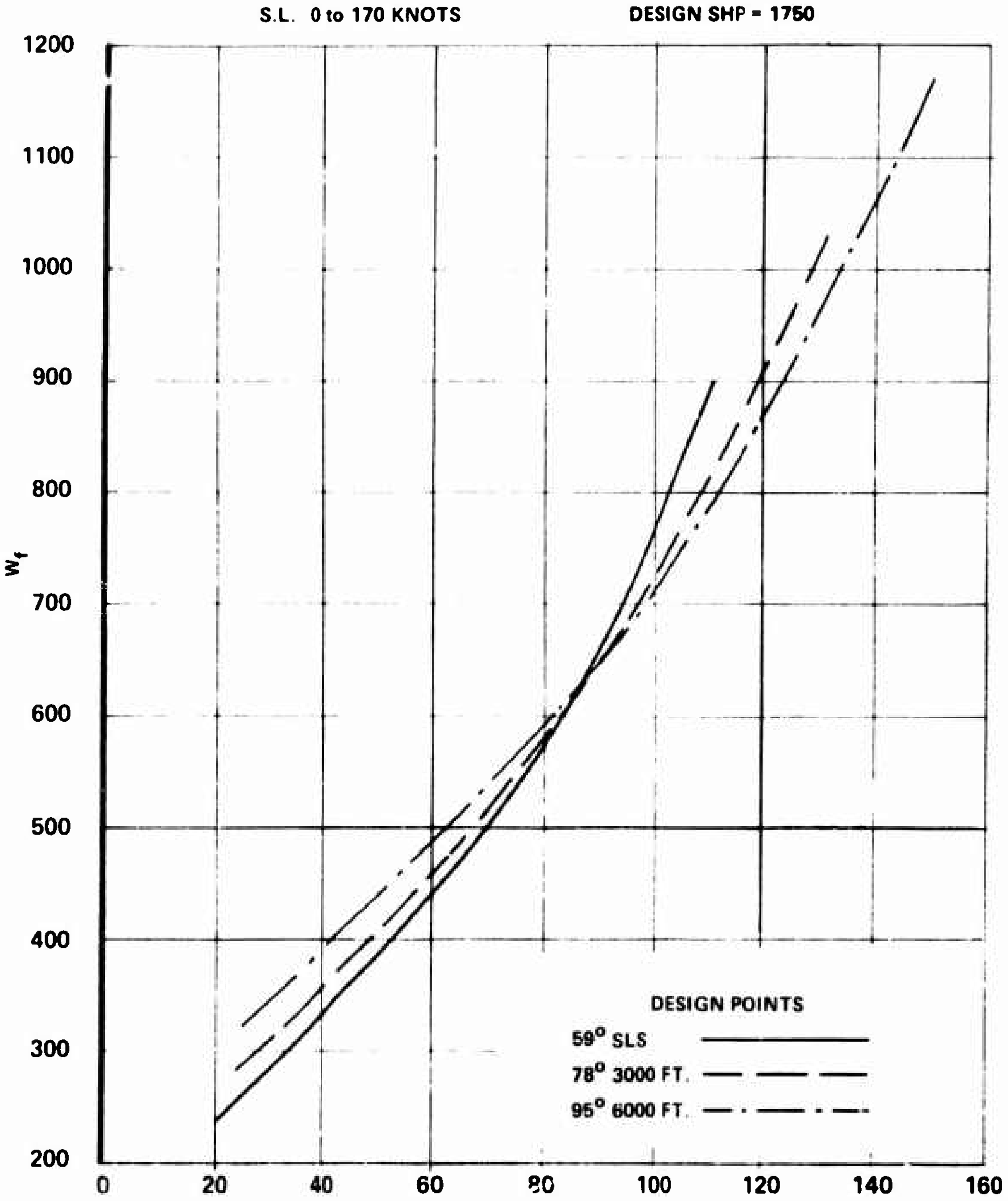


Figure 62. Inter-turbine regenerative engine fuel flow versus percent design shaft horsepower.

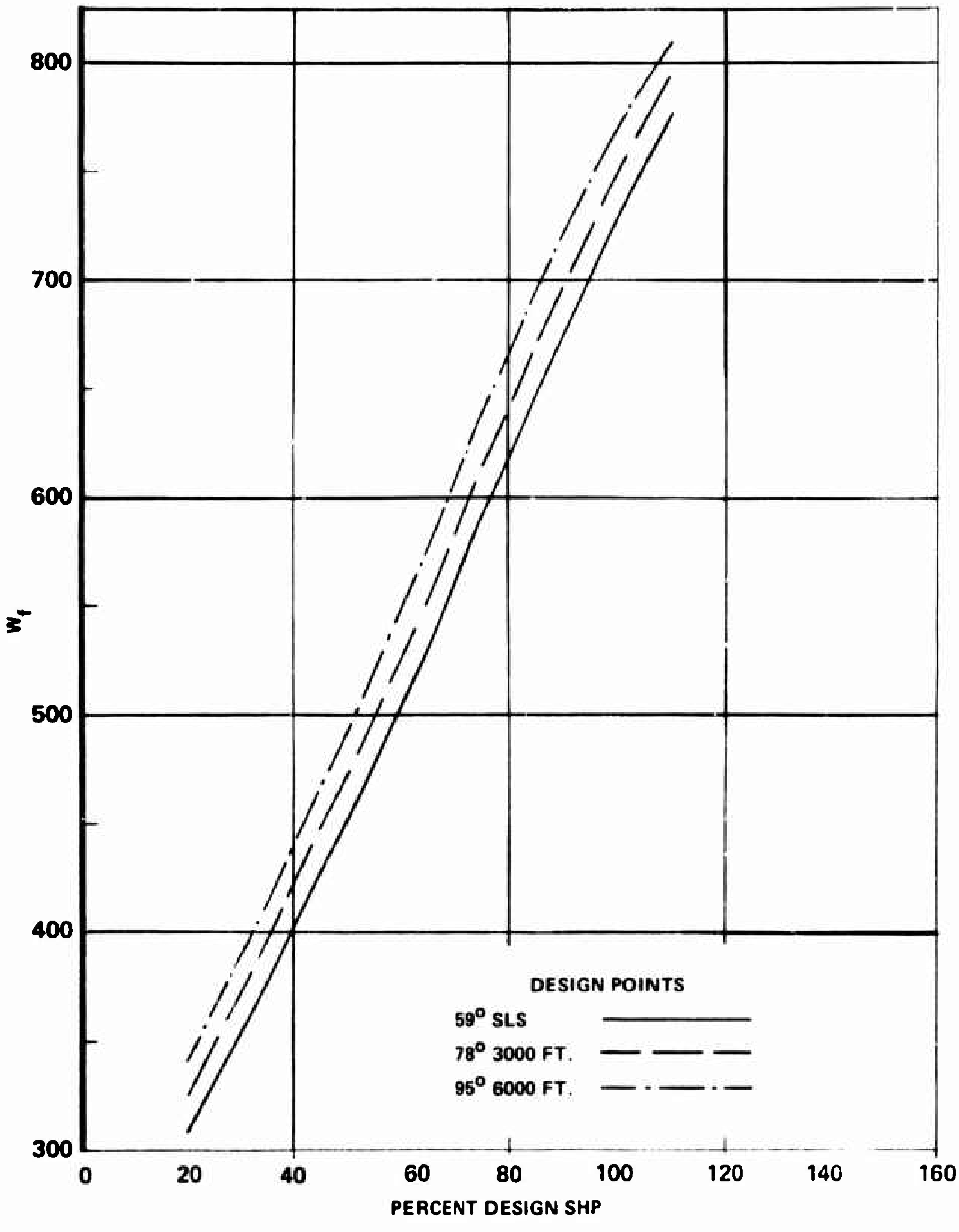


Figure 63. Non-regenerative engine fuel flow versus percent design shaft horsepower.

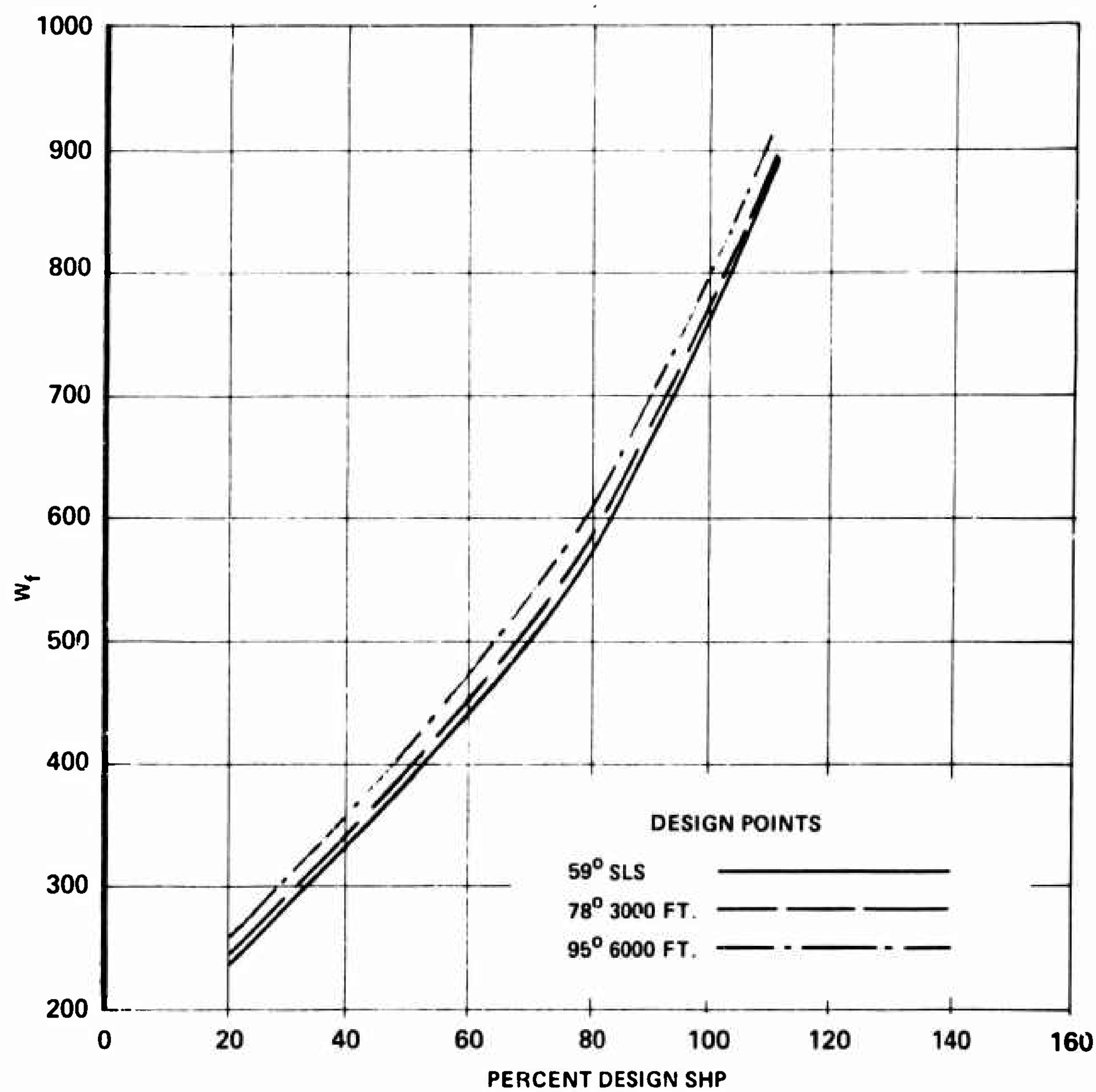


Figure 64. Inter-turbine regenerative engine fuel flow versus percent design shaft horsepower.

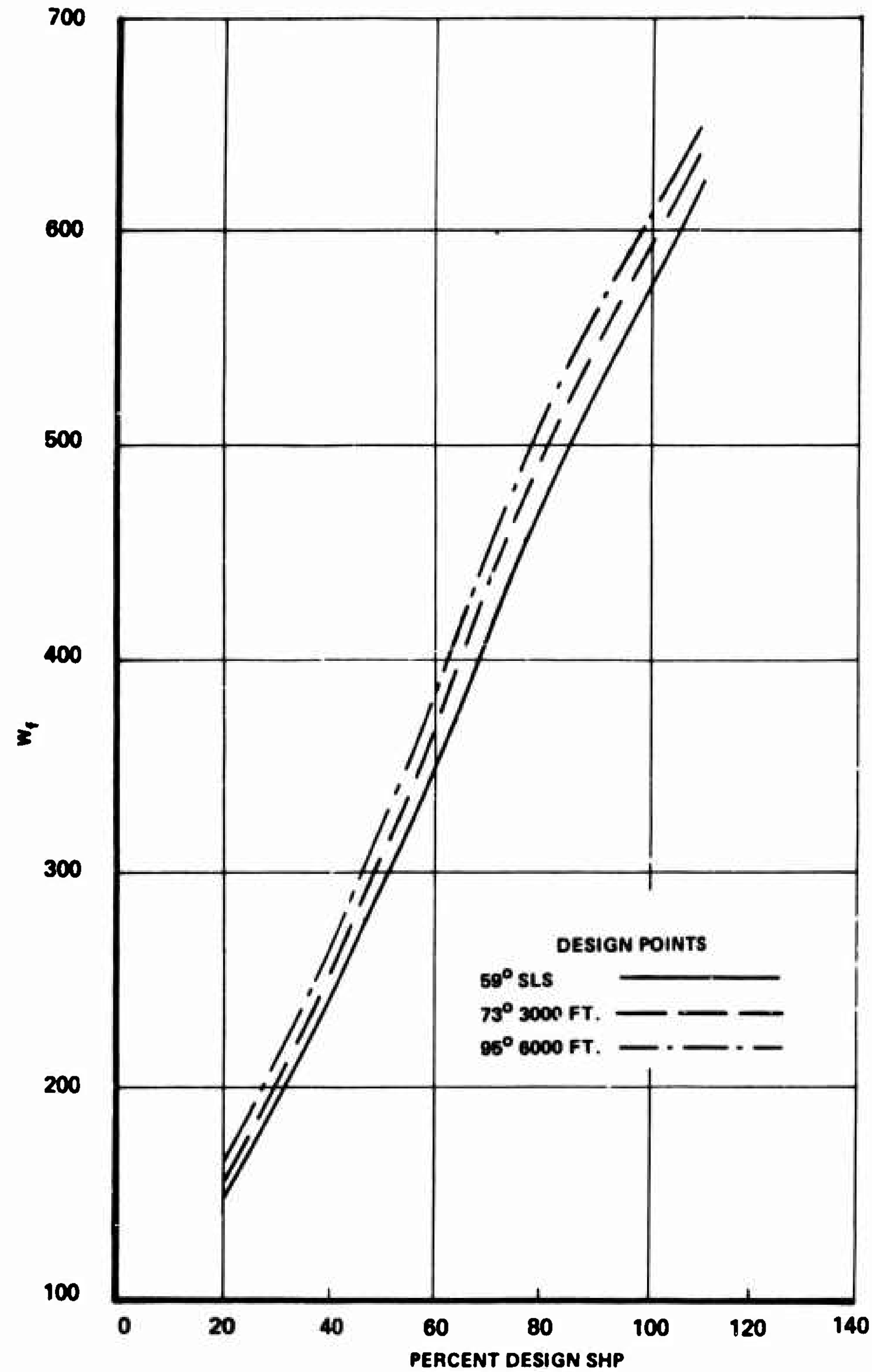


Figure 65 Post-turbine regenerative engine fuel flow versus percent design shaft horsepower.

TABLE XIX

NON-REGENERATIVE ENGINE

MISSION FUEL REQUIREMENTS - POUNDS

Mission Segment	Engine Sizing Condition SL Static 59° F	SL 170 Knots 59° F	3000 Ft Static 78° F	6000 Ft Static 95° F	SL Static 59° F Emergency Power
Takeoff*	49	54	58	66	71
Cruise Out	293	302	317	345	374
Trip No. 1	286	296	303	335	365
Trip No. 2**	373	365	390	420	446
Trip No. 3	273	280	293	321	349
Loiter and Reserve	313	329	354	412	469
TOTAL	1587	1626	1715	1899	2074***

* Power required is 1704 SHP/engine with an augmentation system assumed to be available for power-deficient engines.

** The lower value of maximum cruise or 170 knots.

*** On a two-engine basis, this figure is 4148 pounds; however, if it is allowable to operate on one engine during cruise and loiter, this total could be reduced to 3265.7 pounds.

SAMPLE CALCULATION OF MERIT FACTOR
FOR TAKEOFF AT 6000 FT, 95°F

NON-REGENERATIVE ENGINE
DESIGN POINT: SEA LEVEL 59°F
AUGMENTATION SYSTEM: PRE-COMPRESSOR
WATER-ALCOHOL INJECTION

$$MF = (W_E \times 1.25) + W_{FM}$$

1. From Table V, the base engine weight for this engine, W_{EB}, is

$$W_{EB} = 290 \text{ lb}$$

2. Scaling the engine to 1704 horsepower, the scaled weight W_{EB} is

$$W_{EB'} = (W_{EB}) \left(\frac{1704}{SHP_D}\right)^{1.2\,*}$$

$$W_{EB'} = (290) \left(\frac{1704}{1704}\right)^{1.2} = 290 \text{ lb}$$

3. From Table XV, the weight of a compressor water-alcohol injection system for this engine, W_A, is

$$W_A = 139 \text{ lb}$$

4. The total weight of the engine and augmentation system is

$$W_E = W_{EB'} + W_A$$

$$= 290 + 139 = 429 \text{ lb}$$

5. The fuel weight W_{FM} from Table XIX is

$$W_{FM} = 1587 \text{ lb}$$

6. Substituting into the merit factor equation

$$MF = W_E \times 1.25 + W_{FM}$$

$$= (429) \times 1.25 + 1587$$

$$MF = 2123 \text{ lb}$$

---

* The scaling exponent used for the regenerative and inter-regenerative engine was 1.1.

TABLE XX

NON-REGENERATIVE ENGINE,

ENGINE-AUGMENTATION SYSTEM MERIT FACTORS FOR

TAKEOFF AT 6000 FT, 95°F DAY - POUNDS*

Augmentation System	Engine Sizing Point SL Static 59°F	 SL 170 Knots 59°F	 3000 Ft Static 78°F	 6000 Ft Static 95°F Day
None	(1950)**	(2025)**	(2173)**	2456
Pre-Compressor Water Injection	2092	2139	2243	-
Pre-Compressor Water-Alcohol Injection	2123	2162	2256	-
Pre-Compressor Ammonia Injection	2305	2301	2363	-
Water-Alcohol Combustor Injection	(2403)**	2461	2476	-
Compressor Intercooling	2346	2356	2388	-
Turbine Overtemperature	(1977)**	2055	2190	-
Combined Over-temperature and Water Injection	2049	2102	2223	-

* Takeoff power required: 1704 SHP/engine

** These figures are shown for reference but do not represent true merit factors, as the system they represent will not supply all the power required for takeoff at 6000 ft 95°F.

SAMPLE CALCULATION OF MERIT FACTOR
FOR EMERGENCY POWER TAKEOFF

NON-REGENERATIVE ENGINE
DESIGN POINT: 6000 FT, 95° F
AUGMENTATION SYSTEM: CHEMICAL FUEL AUXILIARY

1. From Table V, the base engine weight for this engine, W_{EB}, is

$$W_{EB} = 400 \text{ lb}$$

2. Scaling the engine to 1704 horsepower, the scaled weight W_{EB}' is

$$W_{EB}' = (W_{EB}) \left(\frac{1704}{SHP_D}\right)^{1.2}$$

$$= (400) \left(\frac{1704}{1560}\right)^{1.2}$$

$$W_{EB}' = 444.5 \text{ lb}$$

3. From Table XVI, the weight of the augmentation system W_A is

$$W_A = 145 \text{ lb}$$

4. The total weight of two engines and the augmentation system is

$$W_E = (2) \ (W_{EB}') + W_A$$

$$= (2) \ (444.5) + 145$$

$$W_E = 1035 \text{ lb}$$

5. The fuel weight W_{FM} from Table XIX is

$$W_{FM} = 1899 \text{ lb}$$

and for 2 engines,

$$W_{FM} = 3798 \text{ lb}$$

6. Substituting into the merit factor equation,

$$M_F = W_E \times 1.25 + W_{FM}$$

$$= (1035) \times 1.25 + 3798$$

$$M_F = 5092 \text{ lb}$$

TABLE XXI

NON-REGENERATIVE ENGINE,

ENGINE-AUGMENTATION SYSTEM MERIT FACTORS FOR EMERGENCY

TAKEOFF AT SL STANDARD DAY - POUNDS*

Augmentation System	Engine Sizing Point: SL Static 59° F	SL 170 Knots 59° F	3000 Ft Static 78° F	6000 Ft Static 95° F	SL Static 59° F Emergency Power
None	-	-	-	-	5416
Chemical Fuel Auxiliary	4349	4423	4656	5092	-
Chemical Auxiliary with Engine Overtemperature	4230	4283	4514	4966	-
Pre-Compressor Water Injection	-	-	-	4960	-
Combustor Liquid Injection	-	-	-	5124	-
Overtemperature and Pre-Compressor Ammonia Injection	-	-	-	5127	-
Combination System No. 1	4422	4520	4718	-	-
Combination System No. 2	4326	4426	4623	-	-

* Takeoff power required: 1704 SHP/engine.

TABLE XXII

POST-TURBINE REGENERATIVE ENGINE

MISSION FUEL REQUIREMENTS - POUNDS*

Mission Segments	Engine Sizing Condition SL Static 59°F	 3000 Ft Static 78°F	 6000 Ft Static 95°F	 SL Static 59°F Emergency Power
Takeoff*	36	44	49	51
Cruise Out	216	223	225	219
Trip No. 1	205	210	214	210
Trip No. 2**	286	297	305	297
Trip No. 3	189	194	197	195
Loiter and Reserve	173	178	196	209
TOTAL	1105	1146	1186	1181***

* Assumes an augmentation system available for power-deficient engines.

** The lower value of maximum cruise or 170 knots.

*** On a two-engine basis, 2362 pounds.

TABLE XXIII

POST-TURBINE REGENERATIVE ENGINES,

ENGINE-AUGMENTATION SYSTEM MERIT FACTORS FOR

TAKEOFF AT 6000 FT, 95°F DAY*

Augmentation System	Engine Sizing Point SL Static 59°F	 3000 Ft Static 78°F	 6000 Ft Static 95°F
None	(2242)**	(2526)**	2731
Pre-Compressor Water Injection	2359.5	2565	-
Pre-Compressor Water-Alcohol Injection	2384.5	2573	-
Combined Water Injection and Turbine Overtemperature	2327	-	-
Turbine Inlet Overtemperature	(2270)**	2542	-
Pre-Compressor Ammonia Injection	2500	2615	-
Combustor Water-Alcohol Injection	2596	2657	-

* Takeoff power required: 1520 SHP/engine

** These figures are shown for reference but do not represent true merit factors, as the systems they represent will not supply all the power required for takeoff at 6000 ft, 95°F

TABLE XXIV

POST-TURBINE REGENERATIVE ENGINE,

ENGINE-AUGMENTATION SYSTEM MERIT FACTORS FOR

EMERGENCY POWER TAKEOFF AT SL STANDARD DAY - POUNDS*

Augmentation System	Engine Sizing Point SL Static 59°F	3000 Ft Static 78° F	6000 Ft Static 95° F	SL Static 59° F Emergency Power
None	-	-	-	6271
Chemical Fuel Auxiliary	4851	5311	5626	-
Chemical Auxiliary with Engine Overtemperature	4745	5197	5547	-
Overtemperature and Combustor Injection	-	5333	5727	-
Overtemperature and Pre-Compressor Ammonia Injection	-	5232	5592	-
Combination System No. 2	5169	-	-	-

* Takeoff power required: 1520 SHP/engine

TABLE XXV

INTER-TURBINE REGENERATIVE ENGINE

MISSION FUEL REQUIREMENTS - POUNDS *

Mission Segment	Engine Sizing Point SL Static 59° F	3000 Ft Static 78° F	6000 Ft Static 95° F	SL Static 59° F Emergency Power
Takeoff**	51	62	66	63
Cruise Out	263	270	280	306
Trip No. 1	250	258	269	295
Trip No. 2***	382	358	354	375
Trip No. 3	235	245	253	280
Loiter and Reserve	256	282	311	363
TOTAL	1436	1475	1532	1682****

* Takeoff power required: 1750 SHP/engine.

** Assumes an augmentation system available for power-deficient engines.

*** The lower value of maximum cruise or 170 knots.

**** On a two-engine basis, 3364 pounds.

TABLE XXVI

INTER-TURBINE REGENERATIVE ENGINE, COMPARISON OF INSTALLED WEIGHT OF ENGINE AND MISSION FUEL FOR AN ENGINE WITH NC REGENERATOR BYPASSING SIZED AT SEA LEVEL STATIC ON A STANDARD DAY, AND AN ENGINE WITH FULL REGENERATOR BYPASSING SIZED AT 6000 FT, 95° F DAY - POUNDS*

Mission Segment	Engine Sizing Conditions SL Static 59° F No Bypass	 6000 Ft Static 95° F Full Bypass
Takeoff	48	66
Cruise Out	284	280
Trip No. 1	271	269
Trip No. 2	354	354
Trip No. 3	258	253
Loiter and Reserve	313	311
TOTAL	1528	1532
Installed Engine Weight	1360	1290
Merit Factor	2888	2822

* Takeoff power required: 1750 SHP/engine.

TABLE XXVII

INTER-TURBINE REGENERATIVE ENGINE,

ENGINE-AUGMENTATION SYSTEM MERIT FACTORS FOR

TAKEOFF AT 6000 FT, 95° F DAY - POUNDS*

Augmentation System	Engine Sizing Point SL Static 59° F	 3000 Ft Static 78°F	 6000 Ft Static 95°F
None	(2336)**	(2579)**	2822
Pre-Compressor Water Injection	2481	2650	-
Pre-Compressor Water-Alcohol Injection	2512	2664	-
Pre-Compressor Ammonia Injection	2698	2773	-
Water-Alcohol Combustor Injection	(2798)**	2868	-
Turbine Overtemperature	(2358)**	2595	-
Combined Over-temperature and Water Injection	2437	2630	-

* Takeoff power required: 1750 SHP/engine.

** These figures are shown for reference but do not represent true merit factors as the systems they represent will not supply all the power required for takeoff at 6000 ft, 95° F

TABLE XXVIII

INTER-TURBINE REGENERATIVE ENGINE,

ENGINE-AUGMENTATION SYSTEM MERIT FACTORS FOR

EMERGENCY TAKEOFF AT SL STANDARD DAY - POUNDS*

Augmentation System	Engine Sizing Point			
	SL Static 59° F	3000 Ft Static 78° F	6000 Ft Static 95° F	SL Static 59° F Emergency Power
None	-	-	-	6828
Chemical Fuel Auxiliary	5133	5476	5975	-
Chemical Auxiliary with Overtemperature	5020	5342	5700	-
Pre-Compressor Water Injection	-	-	5694	-
Combustor Liquid Injection	-	-	5861	-
Overtemperature and Pre-Compressor Ammonia Injection	-	-	5864	-
Combination System No. 1	5210	5541	-	-
Combination System No. 2	5111	5443	-	-

* Takeoff power required: 1750 SHP/engine.

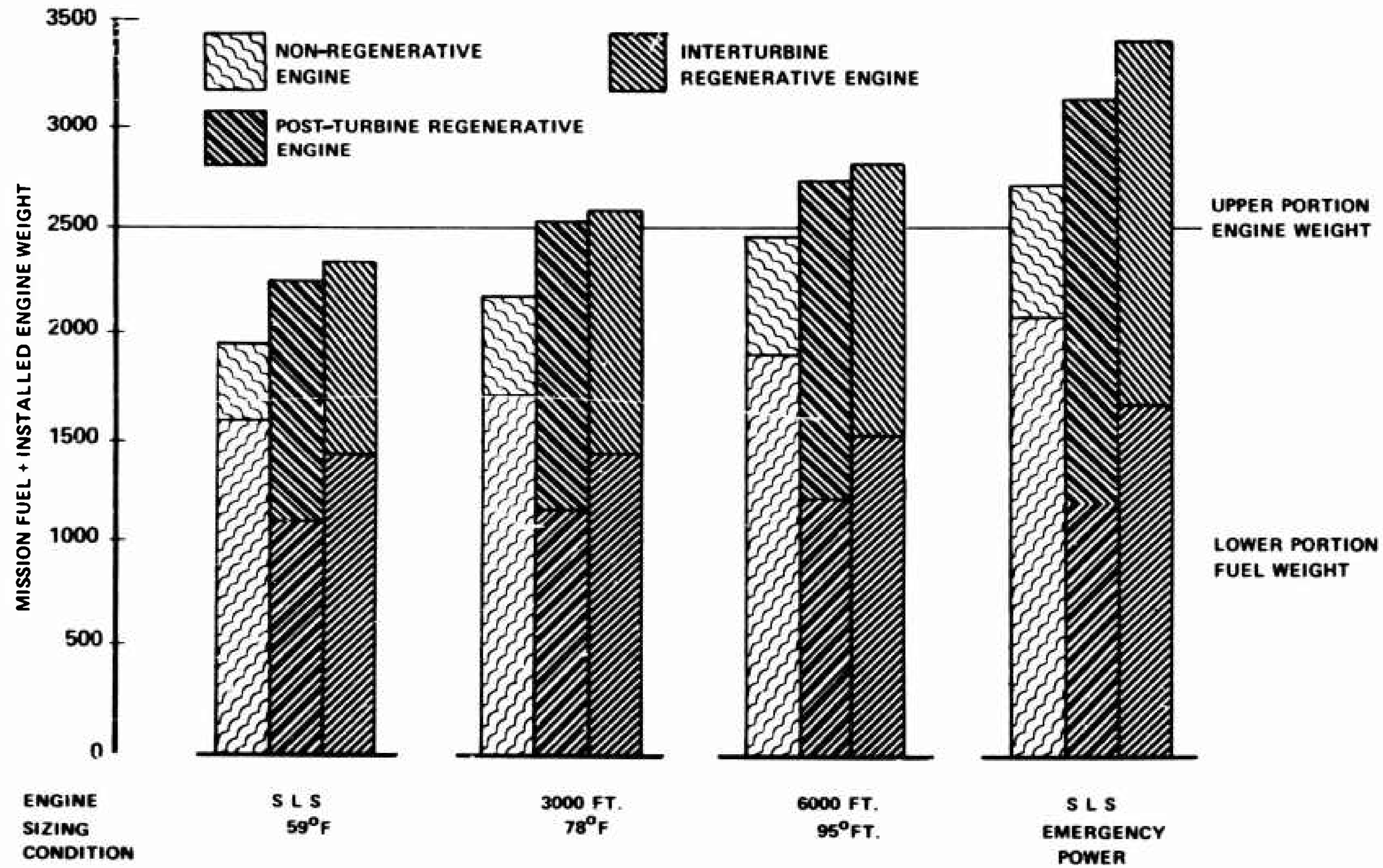


Figure 66. Unaugmented system total weight/engine.

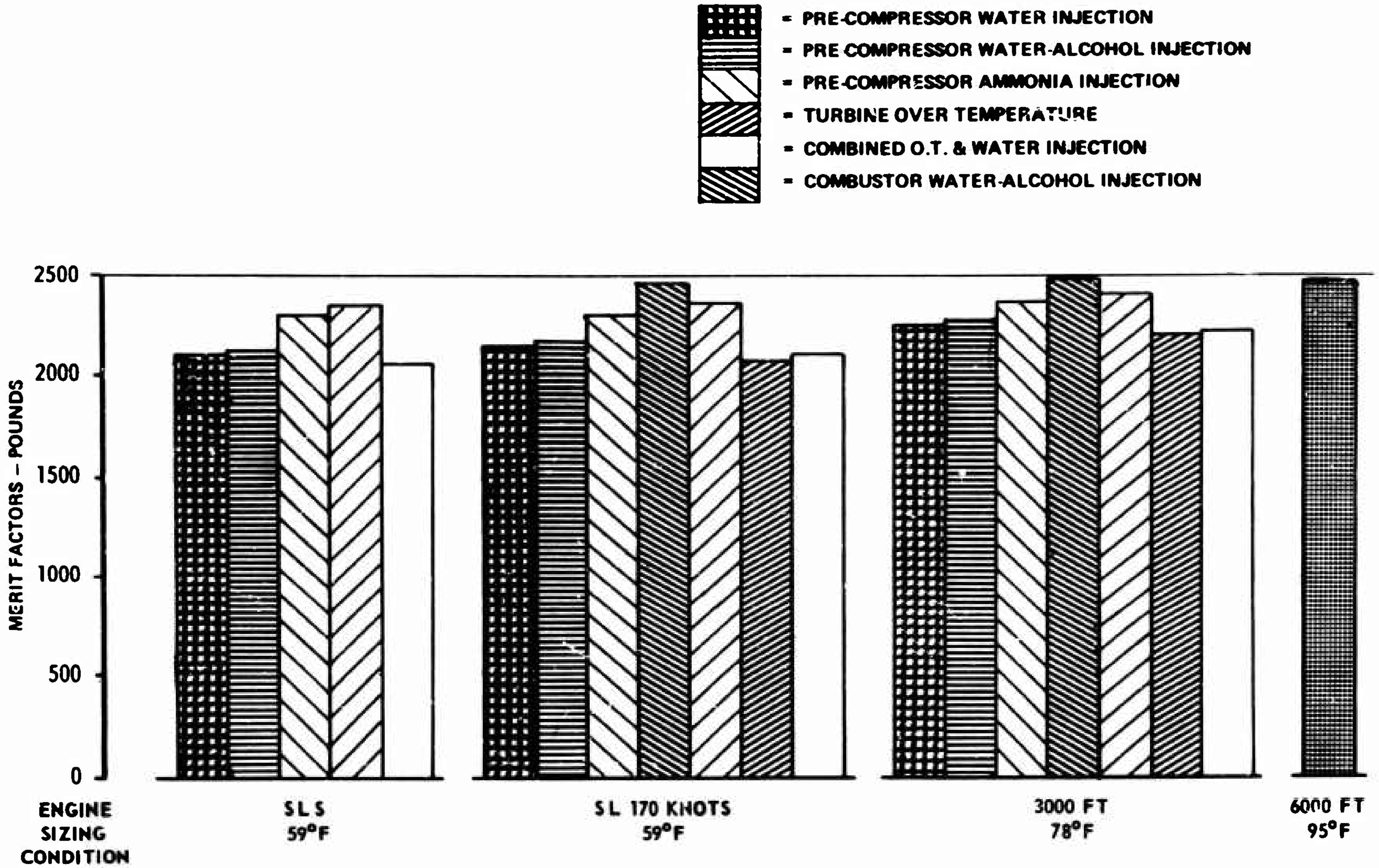


Figure 67. Augmentation system merit factors, 6000 feet, T ambient = 95°F, non-regenerative engine.

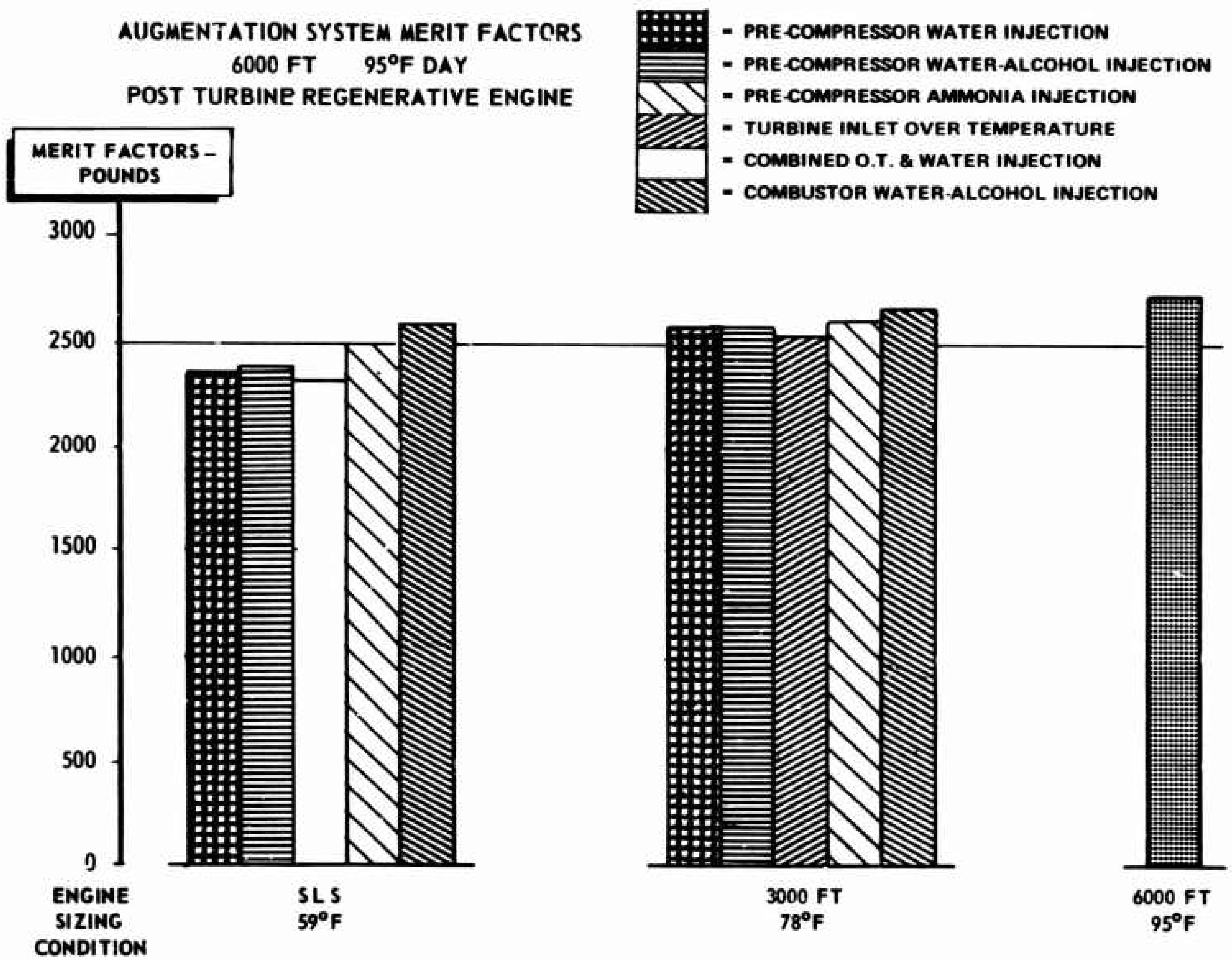


Figure 68. Augmentation system merit factors, 6000 feet, T ambient = 95°F, post-turbine regenerative engine.

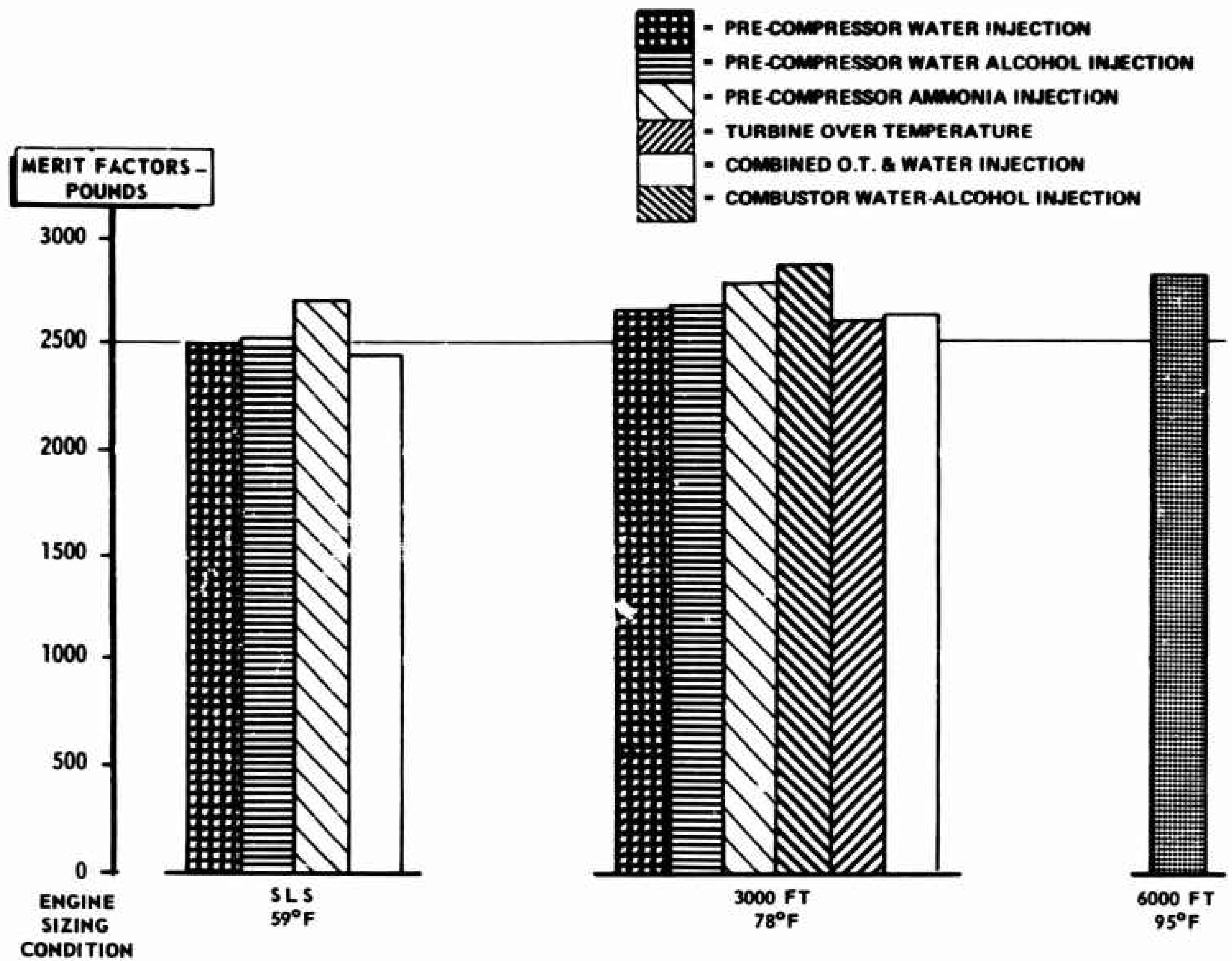


Figure 69. Augmentation system merit factors, 6000 feet, T ambient = 95°F, inter-turbine regenerative engine.

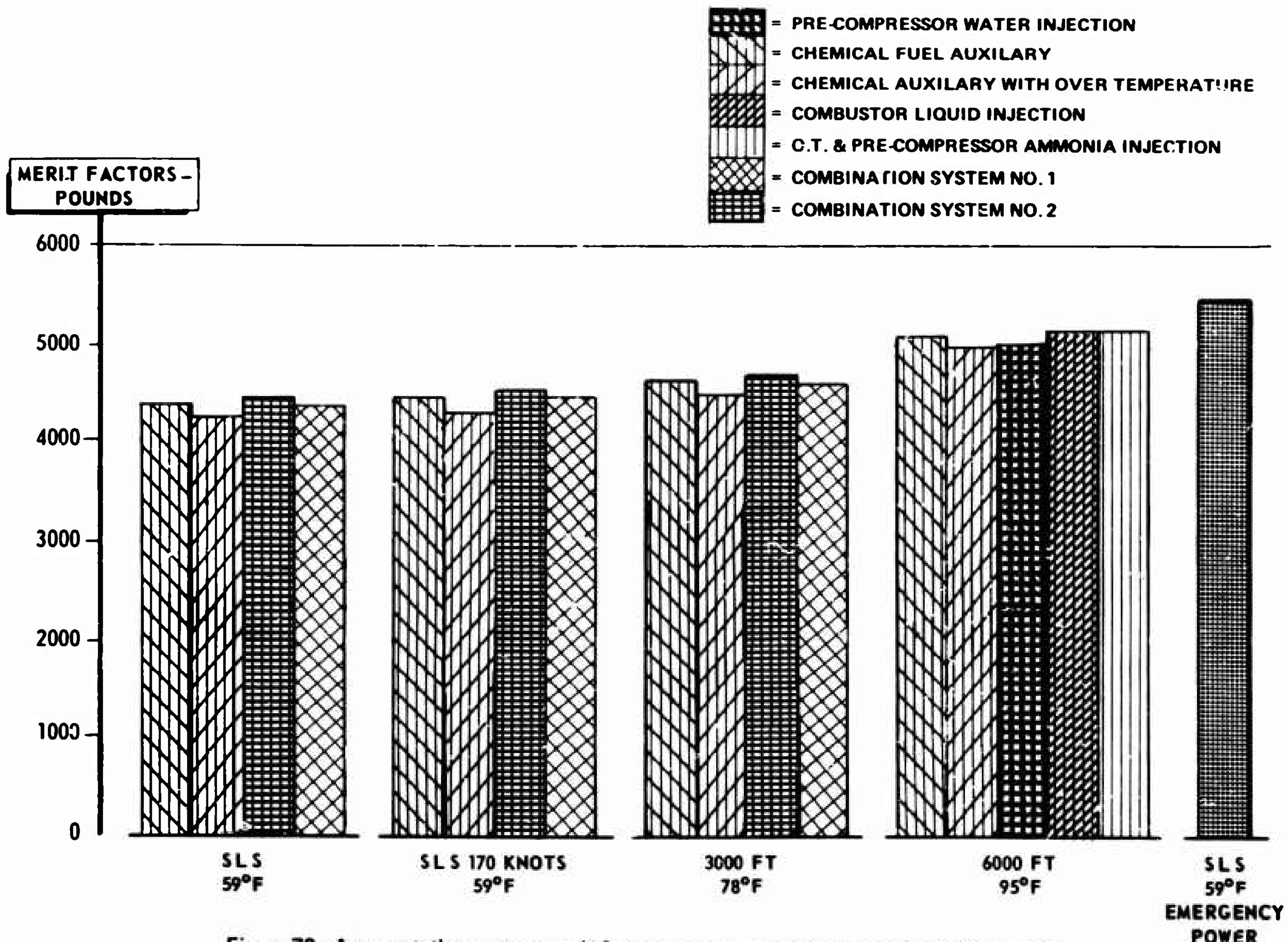


Figure 70. Augmentation system merit factors, emergency power, non-regenerative engine.

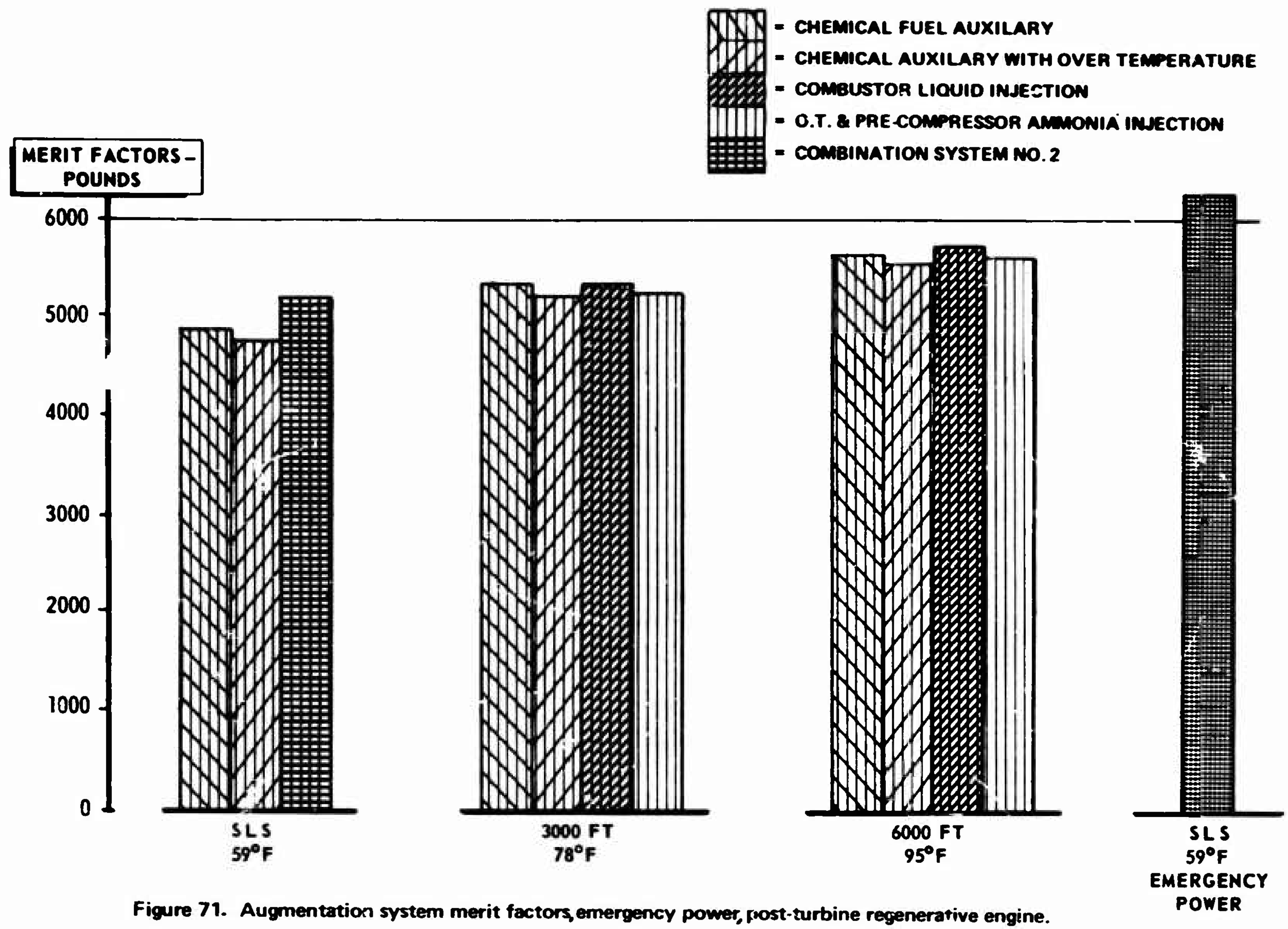


Figure 71. Augmentation system merit factors, emergency power, post-turbine regenerative engine.

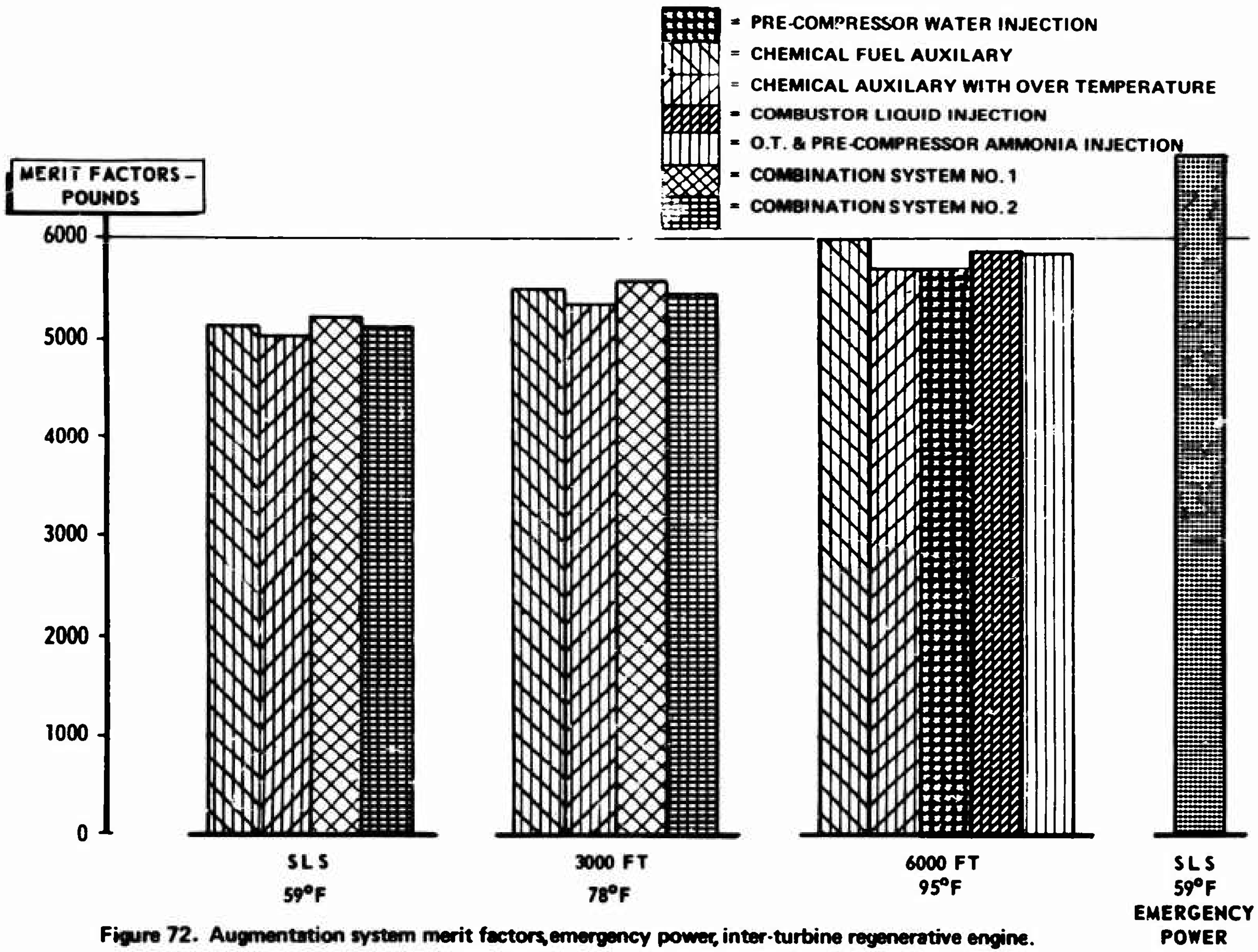


Figure 72. Augmentation system merit factors, emergency power, inter-turbine regenerative engine.

KEY TO COMBINED AUGMENTATION SYSTEM BAR GRAPHS

Emergency Power Systems

1 Chemically Fueled Auxiliary

2 Chemically Fueled Auxiliary with Engine Overtemperature

3 Combination System No. 1

4 Combination System No. 2

5 Overtemperature and Combustor Liquid Injection

6 Overtemperature and Pre-Compressor Ammonia Injection

7 Compressor Water-Alcohol Injection

6000 Ft, 95° F Day Systems

.1 Pre-Compressor Water Injection

.2 Turbine Inlet Overtemperature

.3 Combined Overtemperature and Water Injection

.4 Engine Sized at 6000 Ft, 95° F

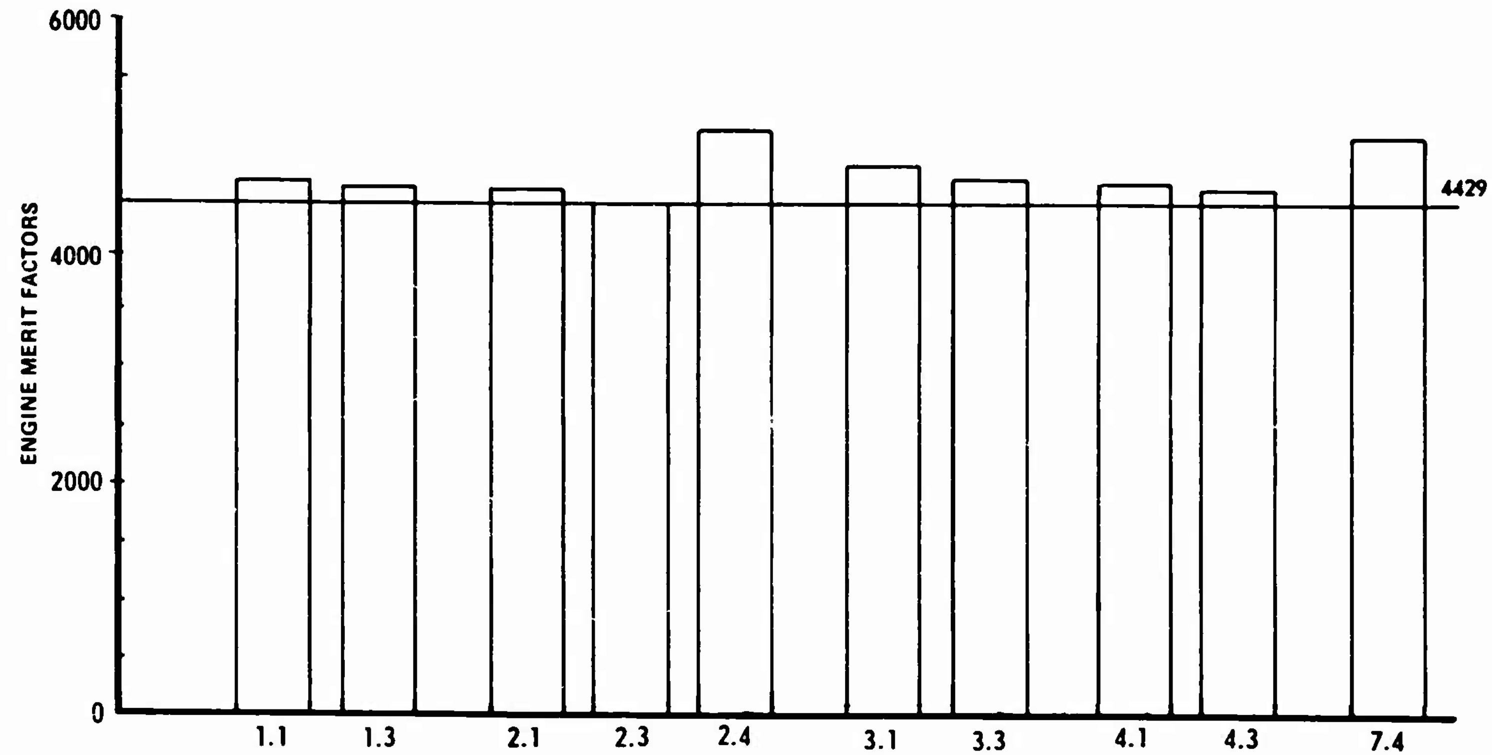


Figure 73. Augmentation system merit factors; combined 6000 feet, T ambient = 95°F and emergency power, non-regenerative engine sized at sea level static, standard day.

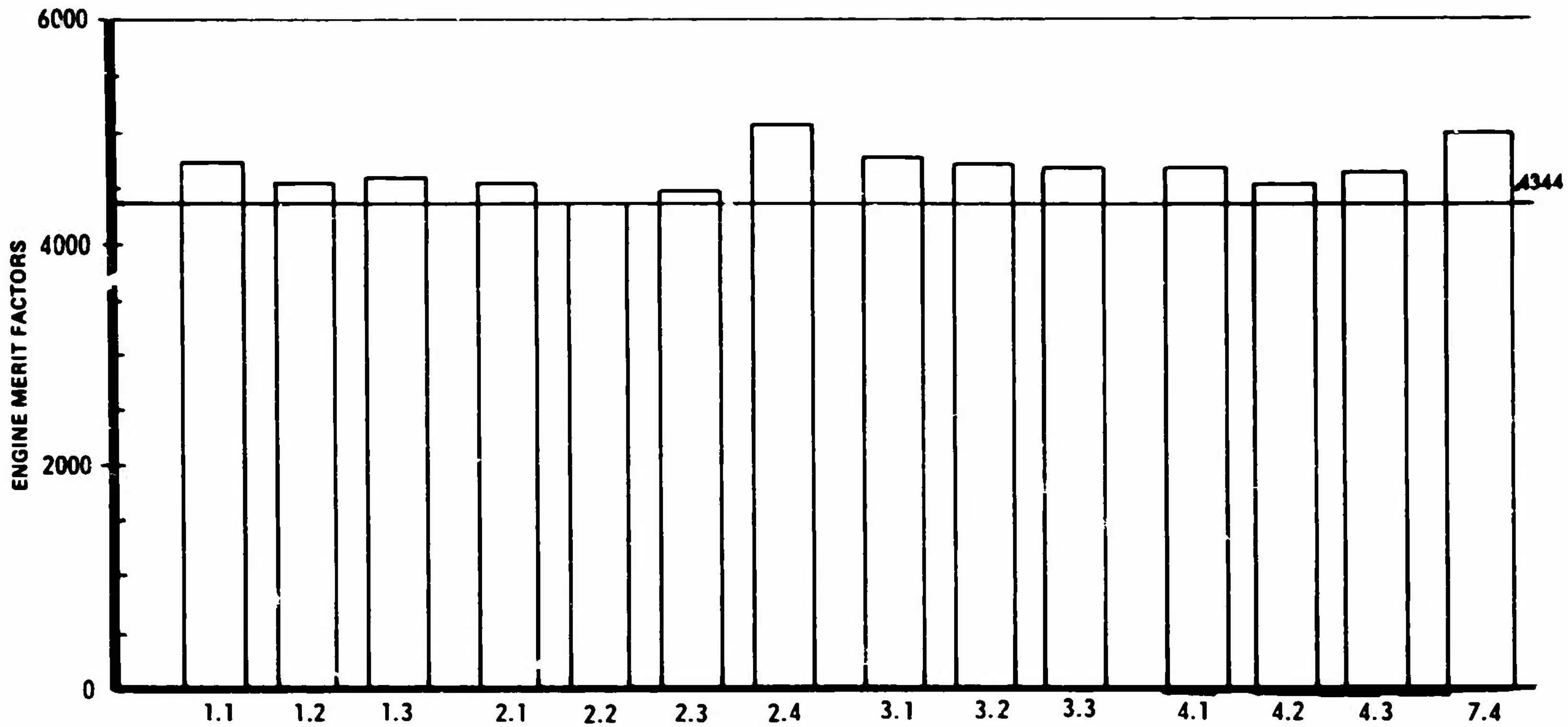


Figure 74. Augmentation system merit factors; combined 6000 feet, T ambient = 95°F and emergency power, non-regenerative engine sized at sea level 170 knots, standard day.

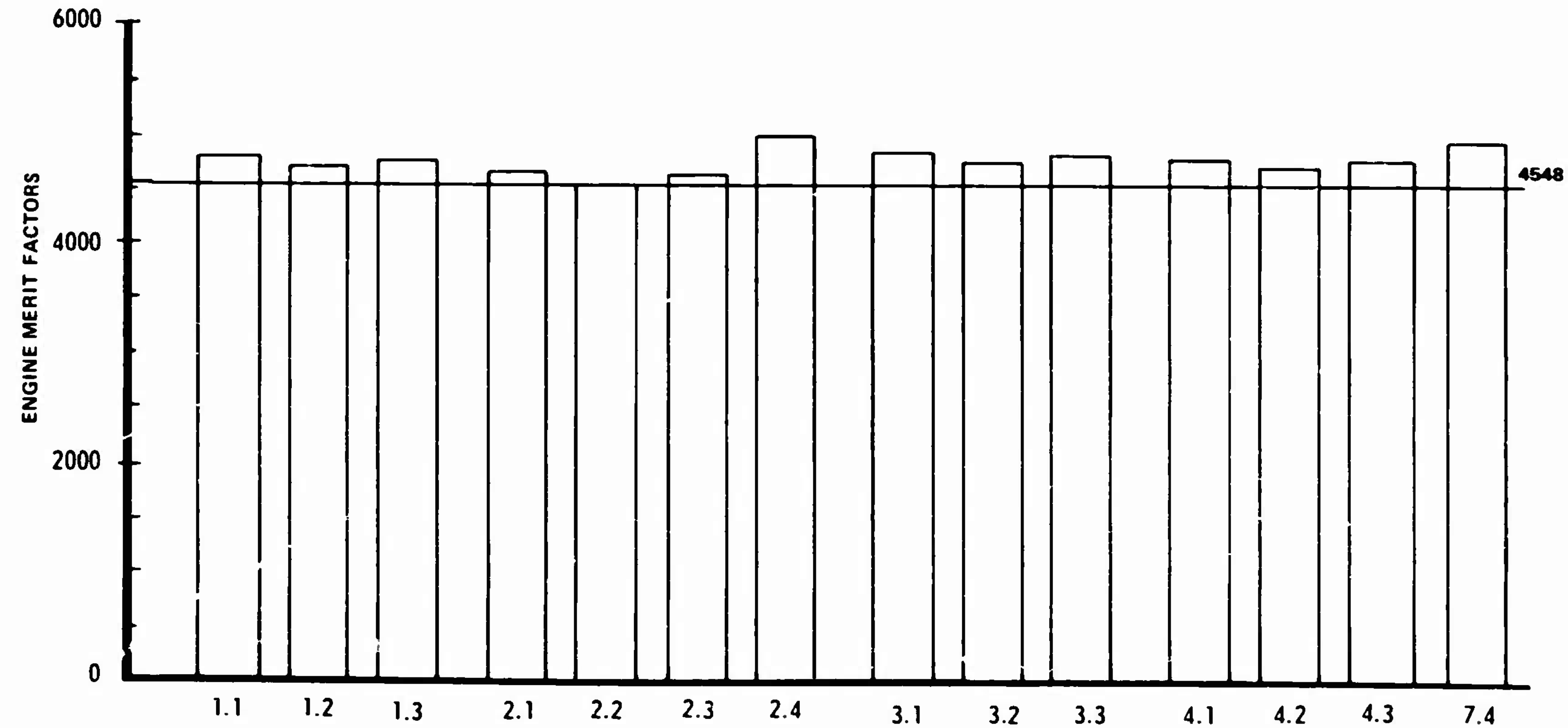


Figure 75. Augmentation system merit factors;combined 6000 feet,T ambient = 95°F and emergency power, non-regenerative engine sized at 3000 feet,T ambient = 78°F.

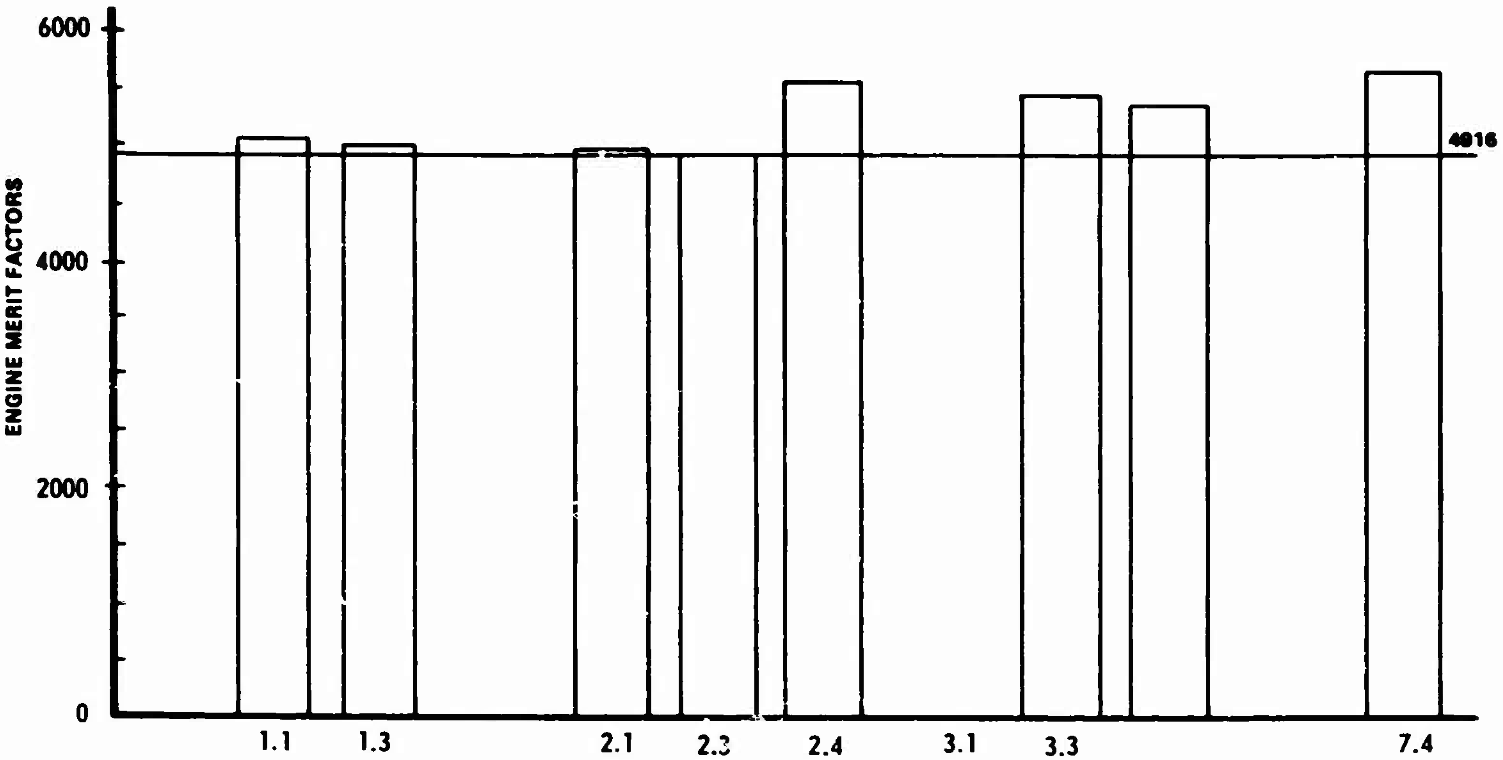


Figure 76. Augmentation system merit factors, combined 6000 feet, T ambient = 95°F and emergency power, post-turbine regenerative engine sized at sea level static, standard day.

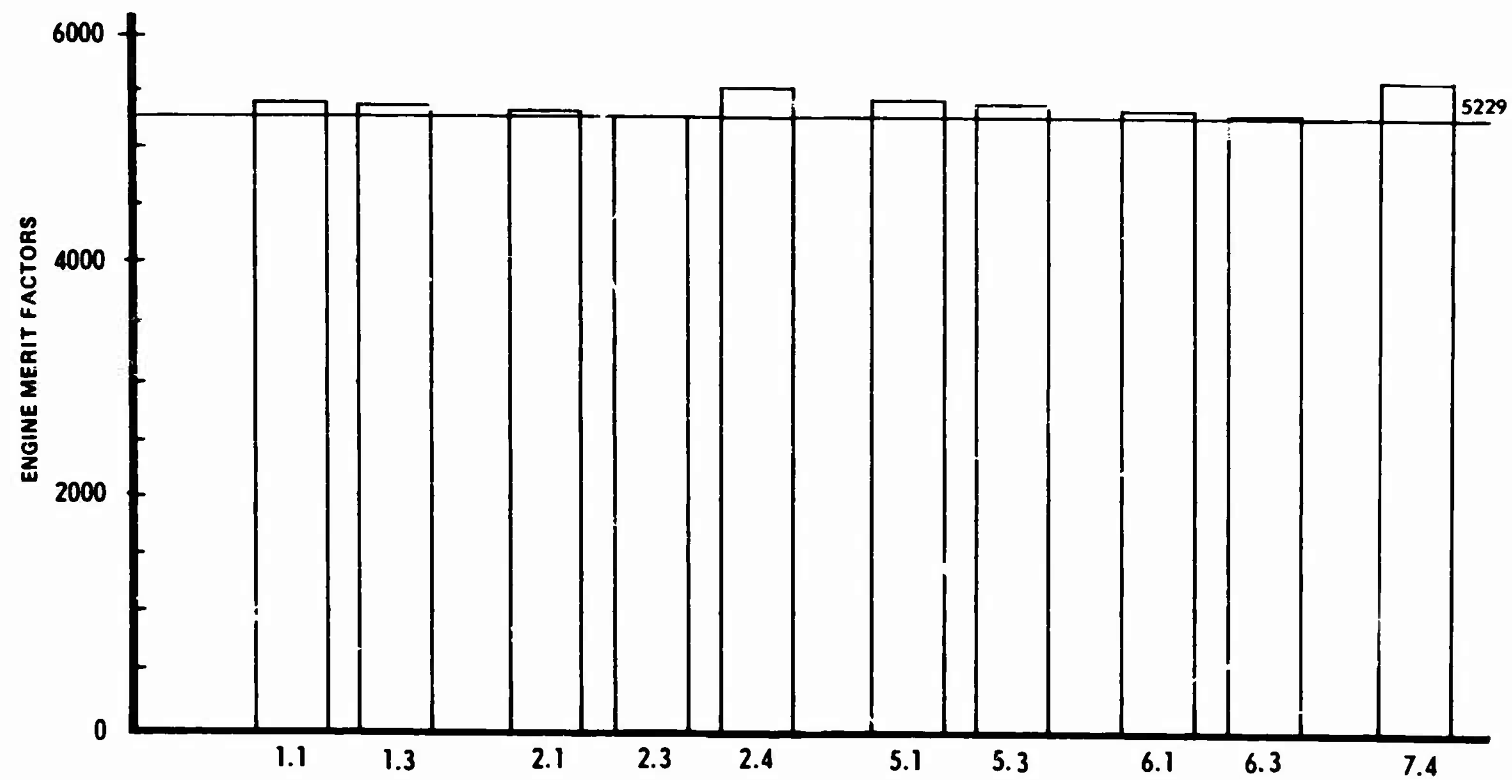


Figure 77. Augmentation system merit factors;combined 6000 feet,T ambient = 95°F and emergency power, post-turbine regenerative engine sized at 3000 feet,T ambient = 78°F.

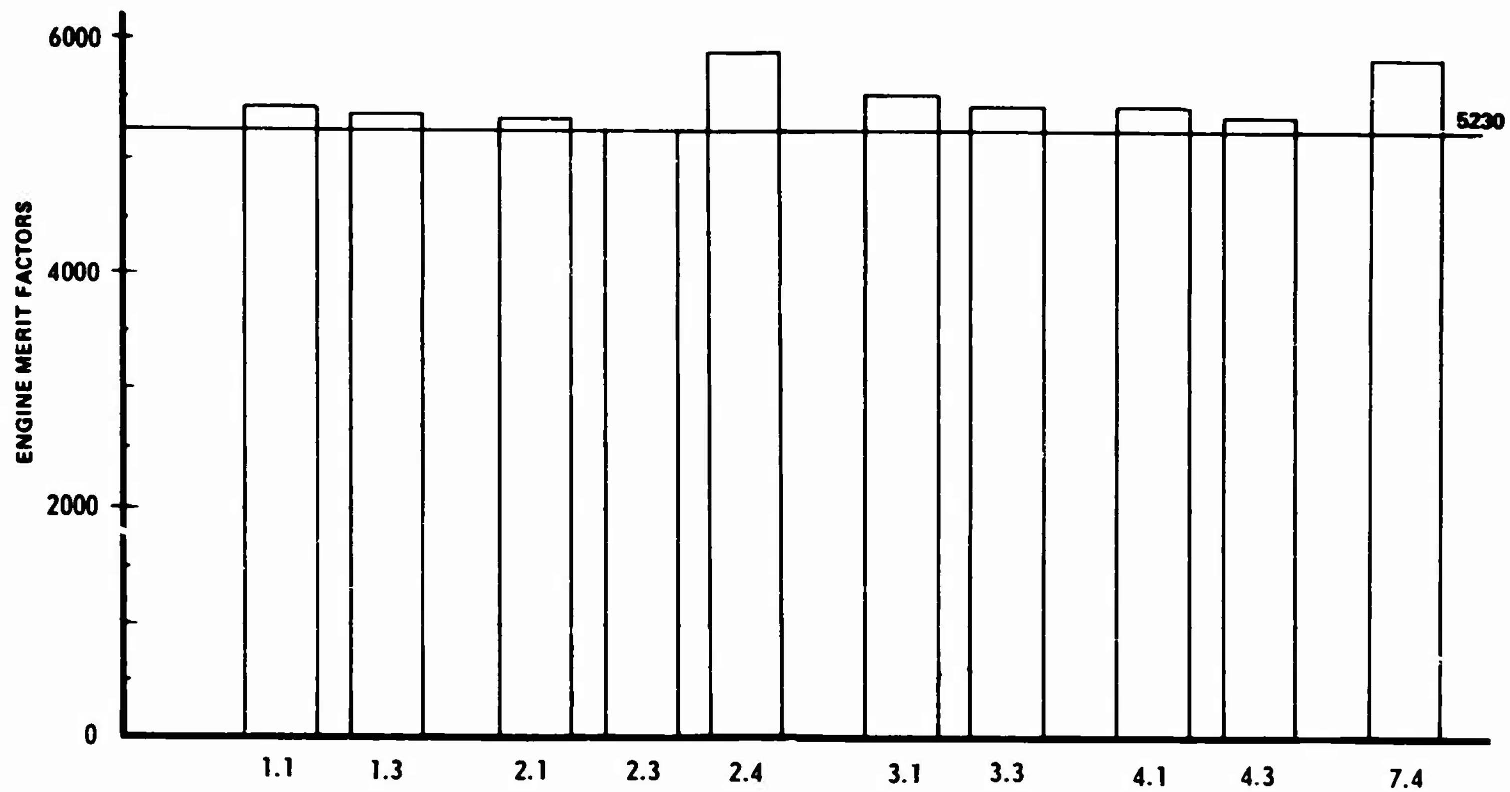


Figure 78. Augmentation system merit factors;combined 6000 feet,T ambient = 95°F and emergency power, inter-turbine regenerative engine sized at sea level static,standard day.

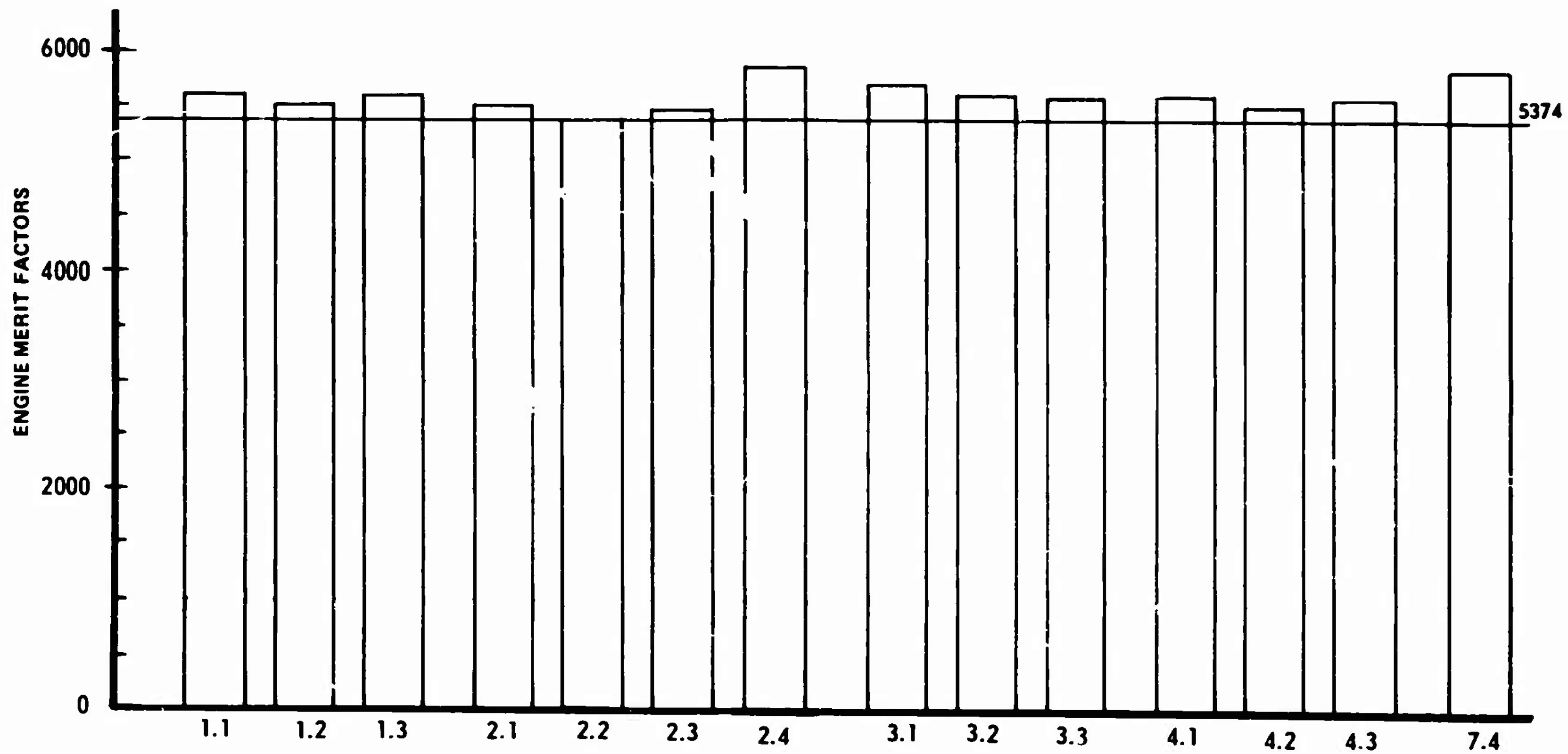


Figure 79. Augmentation system merit factors; combined 6000 feet, T ambient = 95°F and emergency power, inter-turbine regenerative engine sized at 3000 feet, T ambient = 78°F.

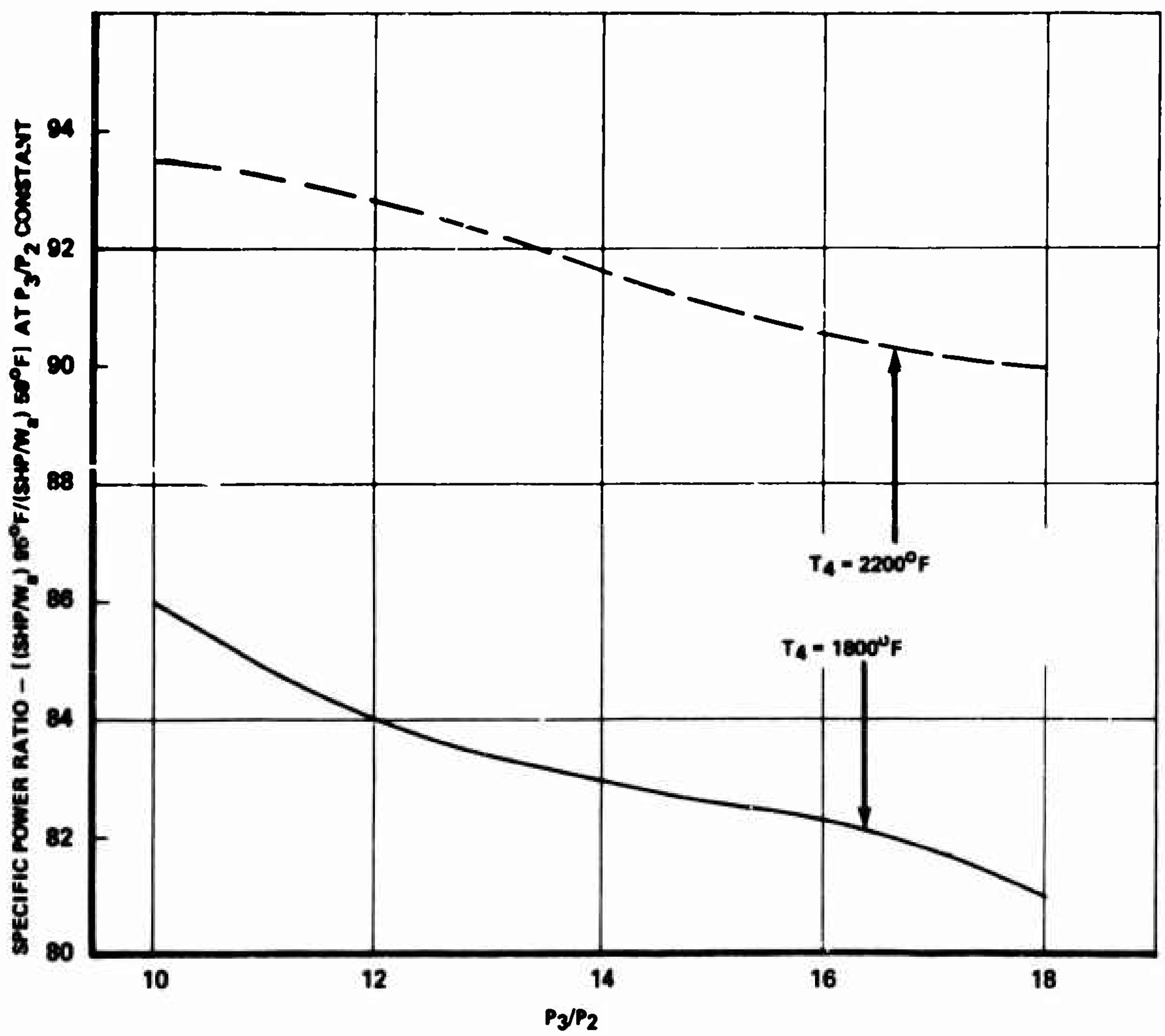


Figure 80. Shaft engine power lapse rate versus pressure ratio as T_2 changes from 59°F to 95°F.

CONCLUSIONS

OPTIMUM METHOD OF PROVIDING ALTITUDE HOT DAY AUGMENTATION

The optimum combinations of an engine and augmentation system to supply power for takeoff from 6000 feet at an ambient temperature of 95°F, when no consideration is given to satisfying the defined emergency power requirement, were a non-regenerative engine size for 10 percent more power than is required for takeoff from sea level on a standard day, with augmentation provided by one of the following systems.

1. Turbine inlet overtemperature where a fuel-cooled heat exchanger is used to reduce the temperature of the combustor and turbine cooling air so that the overtemperature conditions do not compromise the mechanical integrity of the engine.

2. A combination of turbine inlet overtemperature and compressor inlet water injection.

3. Compressor inlet water injection .

The basis for selecting these systems was that they satisfy the power requirements, that they have a low merit factor, that they are simple and require only minor modifications to the engine, and that they would not have any appreciable effects on the unaugmented engine performance. The order of preference in selecting these systems is based on increasing logistics problems in going from number 1 to number 3.

A detailed listing of the advantages, disadvantages, and limitations of each of these systems is contained in the previous section.

OPTIMUM METHOD OF PROVIDING EMERGENCY POWER AUGMENTATION

The optimum method of satisfying the defined emergency power when it is considered independently from hot-day augmentation requirements is to use a non-regenerative engine sized for takeoff from sea level on a standard day, augmented by a combination of turbine inlet overtemperature and a chemically fueled auxiliary. This combination is based on the fact that without the hot-day requirement, the high merit factor associated with a fully oversized engine can not be justified; and of the systems which can provide sufficient augmentation to smaller engines to satisfy the emergency power requirements, the only ones which are technically acceptable are those which use an auxiliary power source to supply the major portion of the augmentation.

OPTIMUM METHODS OF PROVIDING COMBINED HOT DAY ALTITUDE AND ONE-ENGINE-OUT EMERGENCY POWER

Of the various combinations investigated for satisfying the requirements of takeoff from 6000 feet at an ambient temperature of 95°F, and takeoff in emergency one-engine-out situations, the optimum combination of engine and augmentation system was judged to be a non-regenerative engine size for the hot-day altitude condition combined with a compressor inlet water injection system for emergency power augmentation. This system has the highest overall reliability, is simple in design, contains a minimum of additional components, and places no additional maintenance requirements on the engine after use in an emergency situation. Emergency power with this augmentation system is a proven method suitable for long-term standby storage without loss of performance potential and can be readily tested without damaging the engine. The logistics of resupply of the water required are small, and the weight penalty of this system compared to the minimum weight system found was only 10 percent of total installed engine plus fuel weight. A cross-sectional drawing of this engine augmentation system is shown in Figure 81 . Water tank capacity required is 3 gallons, and total augmentation system weight addition is 39 pounds.

PREFERRED ALTERNATE SYSTEMS

One preferred alternate system was a non-regenerative engine sized for a military power output 10 percent higher than required for takeoff from sea level on a standard day, which would use turbine inlet overtemperature for takeoff from 6000 feet on a 95°F day, and a self-contained pre-packaged monopropellant fueled auxiliary power turbine for emergency power requirements. This system required a fuel-cooled heat exchanger to reduce the temperature of the turbine cooling air during hot-day takeoff overtemperature operation, and proof that engine life would not be affected would have to be verified by a test program. This choice of alternate is based on the fact that it is relatively simple in concept, it should be reliable in operation, it satisfied all of the power conditions specified, and it had the lowest total weight of any system found during the study.

The other preferred alternate is a non-regenerative engine sized for sea level on a standard day and using compressor inlet water injection combined with turbine inlet overtemperature for takeoff from 6000 feet on a 95°F day, and the auxiliary engine, turbine inlet overtemperature combination for emergency situations. This system does not need the fuel-cooled heat exchanger and is the second lightest system found, weighing only 1.5 percent more than the lightest system.

INTER RELATIONSHIP BETWEEN ENGINE PHYSICAL OVERSPEED AND AUGMENTATION

For all of the augmentation methods studied except interburning and gas injection into the power turbine, engine overspeed accompanied the augmentation unless there was some method of preventing it, such as the use of a variable turbine or of a clutch to tie the gas generator to the load. It is then apparent that if a free-turbine shaft engine is to be augmented, it must have built-in physical overspeed capability in the gas generator.

EFFECT OF THE MISSION MODEL USED ON THE CHOICE OF THE OPTIMUM METHOD

The mission model selected directly determined the total fuel weight that went into the merit factor calculations. A mission model which extended over a longer time period or redistributed the portion of time spent on any segment of the mission would change this total. Since the fuel consumed is from 50 to 80 percent of the total weight in the merit factors, any significant changes could affect the type of engine preferred and/or the optimum sizing point.

EFFECT OF THE EMERGENCY POWER REQUIREMENT DEFINITION ON THE RESULTS

As defined, the emergency power requirement called for 80 percent augmentation for an engine sized for takeoff at sea level on a standard day. This requirement eliminated all combinations of basic engine and simple augmentation systems except where engines were sized for the hot-day altitude condition. The multi-component system which could augment the smaller engines to the level required could not be recommended because of its complexity, potential unreliability, and marginal weight advantage.

REGENERATOR BYPASSING AS AN AUGMENTATION METHOD

Augmentation is not obtained by bypassing the regenerator component of a regenerative engine unless the regenerator is large enough to allow the engine to reach military power without the use of the bypass. Designing the regenerator in this manner, however, resulted in a regenerator weight which was so high that the regenerative engine had unacceptably poor merit factors even though its total fuel consumption was low.

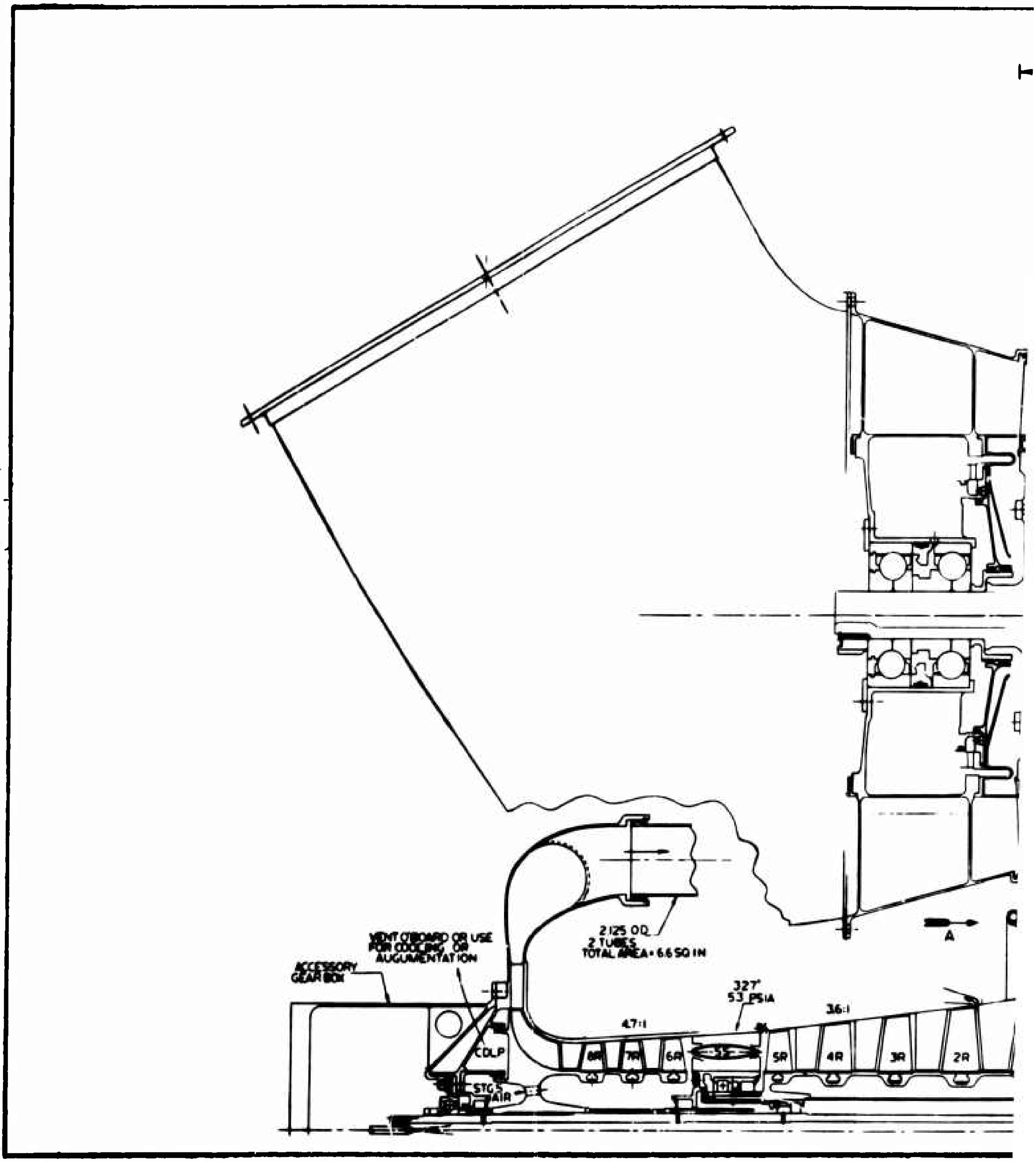
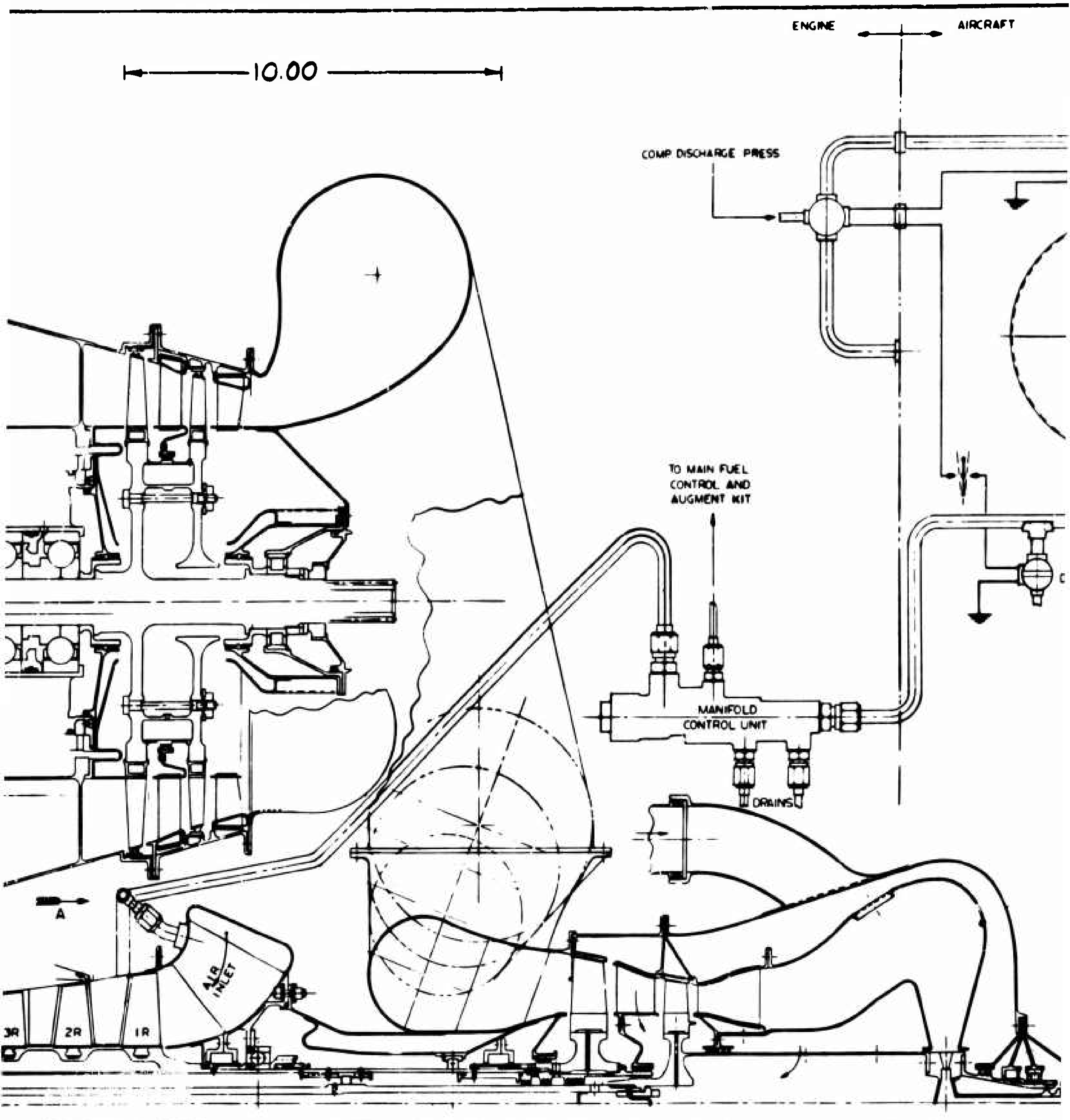


Figure 81. Optimum combined engine - augmentation system.


ENGINE
AIRCRAFT
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TO MAIN FUEL CONTROL AND AUGMENT KIT
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3R
2R
1R

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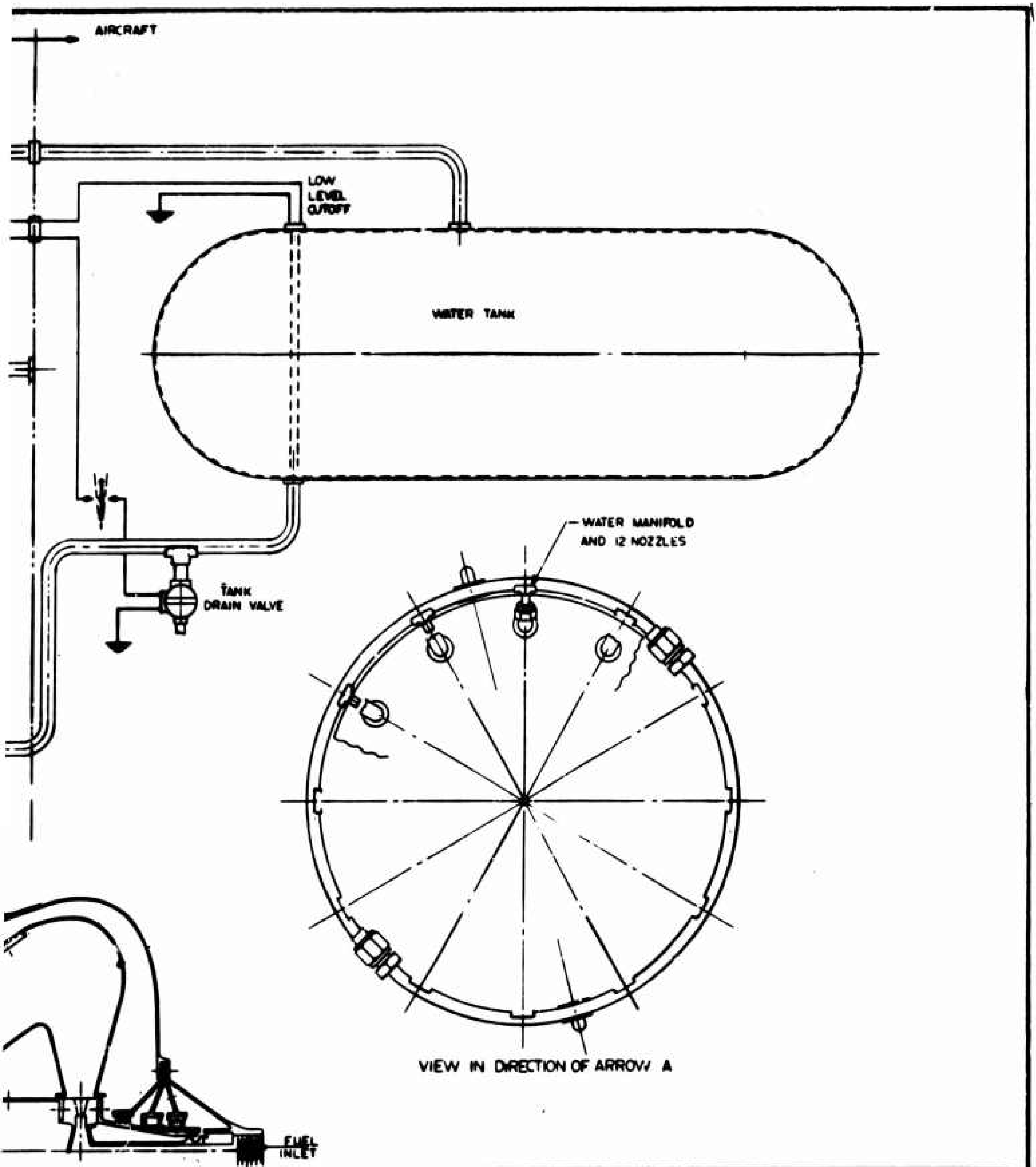

AIRCRAFT
LOW
LEVEL
CUTOFF
WATER TANK
TANK
DRAIN VALVE
WATER MANIFOLD
AND 12 NOZZLES
VIEW IN DIRECTION OF ARROW A
FUEL
INLET

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13. ABSTRACT

Methods of obtaining altitude hot day and emergency one-engine-out power augmentation were analyzed to determine the characteristics of combined engine-augmentation systems which were capable of satisfying the divergent vehicle-engine power matching requirements of helicopter-type vehicles at minimum cruise, takeoff from 6000 feet at an ambient temperature of 95°F and emergency one-engine-out takeoff.

The combined engine-augmentation systems which satisfied these requirements were then rated on the basis of their complexity; any advantages, disadvantages, and limitations associated with their use; and a merit factor based on the total installed system and fuel weight required to perform a typical mission.

Based on the results of these studies selections were made of the engine-augmentation systems which were optimum for supplying altitude hot day takeoff power only, emergency one-engine-out takeoff power only, and both types of augmentation from a single system.

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Power augmentation Systems						
Helicopter Engines						
Hot day performance requirements						
Emergency Power requirements						